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# **FPETOOL: Fire Protection Engineering Tools for Hazard Estimation**

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**U.S. Department of Commerce**  
National Institute of Standards and Technology  
Center for Fire Research  
Gaithersburg, MD 20899



*Prepared for:*  
**General Services Administration**  
Public Buildings Service  
Office of Real Property Management and Safety  
Washington, DC 20405



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## CONTENTS

	<u>Page</u>
Abstract	1
1. GENERAL	1
1.1 Introduction	1
1.2 Safety Factors	2
1.3 Objective of Document	3
1.4 Arrangement of Document	3
1.5 Nature of FIREFORM Routines	4
1.6 Nature of MAKEFIRE Routines	5
1.7 Nature of FIRE SIMULATOR	5
1.8 Operational Procedure to Use FPETOOL	7
2. QUALITATIVE OVERVIEW OF PROCEDURES	8
2.1 ENGINEERING ROUTINES USED	8
2.2 FIREFORM	8
2.2.1 ASETBX ROOM MODEL	8
2.2.2 ATRIUM SMOKE TEMPERATURE	8
2.2.3 BUOYANT GAS HEAD	9
2.2.4 CEILING JET TEMPERATURE	9
2.2.5 CEILING PLUME TEMPERATURE	9
2.2.6 EGRESS TIME	10
2.2.7 FIRE/WIND/STACK FORCES ON A DOOR	10
2.2.8 MASS FLOW THROUGH A VENT	11
2.2.9 LATERAL FLAME SPREAD	12
2.2.10 LAW'S SEVERITY CORRELATION	12
2.2.11 PLUME FILLING RATE	13
2.2.12 RADIANT IGNITION OF A NEAR FUEL	13
2.2.13 SMOKE FLOW THROUGH AN OPENING	14
2.2.14 SPRINKLER/DETECTOR RESPONSE	14
2.2.15 THOMAS' FLASHOVER CORRELATION	15
2.2.16 UPPER LAYER TEMPERATURE	15
2.2.17 VENTILATION LIMIT	15
2.3 MAKEFIRE	16
2.3.1 LOOK-EDIT	16
2.3.2 RATES	16
2.3.3 MYFIRE	16
2.3.4 FORMULA	16
2.3.5 FREEBURN	16

2.4	FIRE SIMULATOR	18
2.4.1	Core Model	18
2.4.2	ASET Approach	18
2.4.3	FIRE SIMULATOR Adjustment for Door or Other Opening	19
2.4.4	Calculation of Heat Loss Factors	20
2.4.5	Revisions to Rate of Energy Release	22
2.4.5.1	Oxygen in Smoke Layer	23
2.4.5.2	Oxygen Required for Combustion	23
2.4.5.3	Flame Length	23
2.4.5.4	Effective Diameter of Fire Source	24
2.4.5.5	Fire Plume Temperature	24
2.4.6	Handling Reduction in Oxygen in Primary Combustion Air	25
2.4.7	Handling Excess Fuel	25
2.4.8	Response of Heat Detector (or Sprinklers)	26
2.4.9	Smoke Detector Activation	26
2.4.10	Prediction of Flashover	26
2.4.11	Carbon Monoxide and Carbon Dioxide Concen- trations	26
2.4.12	Vision Distance	27
2.4.13	Post Flashover Burning Rates	28
3.	EQUATIONS USED IN FIREFORM	30
3.1	THE ASETB MODEL	30
3.2	ATRIUM SMOKE TEMPERATURE	32
3.3	BUOYANT GAS HEAD	33
3.4	CEILING JET TEMPERATURE	33
3.5	CEILING PLUME TEMPERATURE	33
3.6	EGRESS TIME	33
3.7	FIRE/WIND/STACK FORCES ON A DOOR	35
3.8	MASS FLOW THROUGH A VENT	36
3.9	LATERAL FLAME SPREAD	36
3.10	LAW'S SEVERITY CORRELATION	37
3.11	PLUME FILLING RATE	37
3.12	RADIANT IGNITION OF A NEAR FUEL	37
3.13	SMOKE FLOW THROUGH AN OPENING	38
3.14	SPRINKLER/DETECTOR RESPONSE	38
3.15	THOMAS' FLASHOVER CORRELATION	40
3.16	UPPER LEVEL TEMPERATURE	40
3.17	VENTILATION LIMIT	41
4.	EQUATIONS USED IN MAKEFIRE	41
4.1	General	41
4.2	Description of Ignition Calculations Involved in Freeburn	41
4.3	Fire Growth Equations used in FORMULA	43



5.	EQUATIONS USED IN FIRE SIMULATOR	44
5.1	Description of the ASETB MODEL	44
5.2	Adjustments for Doors or Other Openings and for HVAC	44
5.2.1	Ventilation Limit	44
5.2.2	Impact of Residual Air on Ventilation Limit	44
5.2.3	Volume Flow	44
5.2.4	Enthalpy losses	45
5.2.5	Impact on the position of smoke layer	45
5.3	Calculation of Heat Loss Factor	46
5.4	Calculation of Combustion Limits Due to Limited Oxygen Availability	49
5.4.1	Limitation due to air supplied from openings and HVAC equipment	49
5.4.2	Limitation due to inability to entrain sufficient air in fire plume	50
5.5	Calculation of Response of Heat Actuated Devices (Sprinklers and Fixed Temperature Heat Detectors)	52
5.6	Calculations for Estimating Response of Smoke Detectors	55
5.7	Calculation for Estimating $O_2$ Concentration in Smoke Layer	55
5.8	Calculations for Estimating CO and $CO_2$ Concentration in Smoke Layer	57
5.9	Estimating Vision Distance in the Smoke Layer	58
6.	ACKNOWLEDGEMENTS	58
7.	REFERENCES	59
	Appendix A. Comparison of results from FPETOOL to test data	65
	Appendix B. Instruction for access and use of the CFRBBS	87
	Appendix C. Carbon Monoxide/Carbon Dioxide Production	93



# FPETOOL - Fire Protection Engineering Tools for Hazard Estimation

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## Abstract

FPETOOL is a computerized package of relatively simple engineering equations and models. A package of engineering tools useful in estimating potential fire hazard and the response of the space and fire protection systems to the developing hazard is presented. The computations use established engineering relationships. This paper outlines those relationships for the benefit of engineers and others interested in using the tools in the package.

## Chapter 1. General

### 1. Introduction.

The FPETOOL package addresses problems related to fire development and the resulting conditions in buildings. In FPETOOL hazardous conditions are expressed in terms of the smoke and hot gas produced by the fire, its location, temperature, obscuration, latent and potential energy, oxygen content, and carbon monoxide and carbon dioxide concentrations. FPETOOL also includes means for estimating egress time; ignition of exposed items; smoke flows; fire, wind, and stack pressures on a door; activation of sprinklers and detectors; and other values useful in the evaluation of fire hazard in building spaces.

FPETOOL is one of several hazard assessment methods produced by the Center for Fire Research of the National Institute of Standards and Technology. Others include the Fire Safety Evaluation Systems (FSES's) now incorporated into the Life Safety Code [1] and HAZARD I [2]. FPETOOL represents an approach that is more analytical than the FSES's and faster but less rigorous than HAZARD I. FPETOOL is also based on a single room approach while HAZARD I has a 6-room capability. While both FPETOOL and HAZARD I predict gas concentrations only HAZARD I predicts toxicity impact of the gases. There are other important differences between FPETOOL and other approaches. Users are advised to review the capabilities and demands of each and to use that most suited to their needs.

The reality of accidental fire is more varied and complex than can be exactly described by a collection of equations and data. The procedures in FPETOOL describe selected relationships between fire and its environment. An attempt has been made to concentrate on the most dominant relationships. It must be expected, however, that real-world situations will include instances where other physical relationships can have important impacts. It is therefore important that the user understand the basic principles being applied by

FPETOOL is designed to approximate rather than exactly predict fire conditions. While the procedures used are based on sound physics or established correlations, simplicity, applicability, and computational speed has been emphasized, with some sacrifice of mathematical rigor. Comparison of the results produced by several of the principle FPETOOL routines with experiential data, (See Appendix A), shows reasonable, but not exact correlation between FPETOOL and experimental results. Users need to consider this in establishing the safety factors to be used when applying FPETOOL.

FPETOOL has three main elements as follows:

1. FIREFORM. FIREFORM is a collection of convenient fire safety calculations. Most of the procedures have been previously issued under the title FIREFORM [3].
2. MAKEFIRE. MAKEFIRE is a series of procedures designed to produce fire data files for use with FIRE SIMULATOR and some of the routines in FIREFORM.
3. FIRE SIMULATOR. FIRE SIMULATOR is an integrated set of equations (i.e. a model) designed to approximate conditions occurring in spaces, response of heat or smoke actuated devices in those spaces, and effluent (energy and fuel) from those spaces to other locations.

FPETOOL is programmed to operate on computers having MSDOS 3.1 or higher operating systems. A computer having 640 kilobytes of memory is needed. It is provided on three double density (360 kilobytes) floppy disks or one high density (1.2 megabyte) floppy disk. The disks contain twelve compiled, executable files, one text file and one README file. The executable files contain all of the various routines for FPETOOL. The README file provides introductory information. The text file is a copy of this report.

FPETOOL requires a hard disk. The minimum disk space needed is 1.2 megabyte. Since the FIRE SIMULATOR portion of FPETOOL and the MAKEFIRE routines produce files, a minimum of 1.5 megabytes is suggested. FPETOOL cannot operate successfully on computers without hard disks. However, many of the individual routines in FIREFORM and MAKEFIRE are available on a separate single floppy disk and can be operated without the hard disk. The computer programs are available to the public on the Center for Fire Research Computer Bulletin Board System (CFRBBS.) Appendix B provides information on using this free public access fire safety resource.

There is also a separate user's guide for loading, starting, and using FPETOOL.

## 2. Safety Factors.

Many of the calculations related to fire development are used in both appraising hazard and estimating the response of fire initiated safeguards. Often both approaches are involved in the same problem. Because of this there is no clear-cut set of conservative assumptions. Also, the procedures in

FPETOOL may, at varying times, be used for a variety of analysis approaches. In view of the above, no safety factor has been built into the computations. Where a safety factor is appropriate (as in design of fire safety for buildings and building occupants) the user must decide on the safety factor and how it is applied. Ways to add safety factors include:

1. Reduction of the calculated time available between knowledge of fire (e.g., operation of a smoke detector) and arrival of an intolerable condition (e.g., flashover);
2. Changing the criteria for the onset of a hazardous condition (e.g., reducing the smoke layer temperature used to indicate the onset of flashover);
3. Increasing the size of the expected initiating fire (normally in terms of rate of growth, peak rate of heat release, and/or duration of burning).

### 3. Objective of Document.

This document outlines the engineering procedures involved in FPETOOL. It is hoped this will provide users with the information needed both to run FPETOOL and to make decisions on how to apply FPETOOL. If not, it is recommended that the user consult with a qualified engineer who can advise on the relationship between the capabilities of FPETOOL, the problem at hand, and the user's specific objectives.

### 4. Arrangement of Document.

This document has five chapters and three appendices.

- a. Chapter 1 describes the general information on arrangement and operational aspects of FPETOOL and its elements.
- b. Chapter 2 is a qualitative discussion of the phenomena handled by FPETOOL and the approach taken. Only a few simple equations are given in chapter 2. The purpose of chapter 2 is to provide a general overview to the processes involved.
- c. Chapter 3 details the individual equations involved in FIREFORM.
- d. Chapter 4 details the individual equations involved in MAKEFIRE.
- e. Chapter 5 details the individual equations involved in FIRE SIMULATOR.
- f. Appendix A provides comparisons of the results obtained from FIRE SIMULATOR with fire test data.
- g. Appendix B gives instructions for access and use of the Center for Fire Research Computer Bulletin Board.

h. Appendix C contains memoranda written by Dr. George Mulholland that underlie the approach taken in FIRE SIMULATOR for estimating carbon monoxide and carbon dioxide production.

i. There also is a separate users guide to assist in the application of the procedures contained in the FPETOOL collection.

#### 5. Nature of FIREFORM Routines.

FIREFORM is a collection of individual procedures called from a common menu. The user may choose to enter input values related to dimensions and temperature in either the English or metric system of units. Output values are expressed in both systems. Since most of the currently available data on burning rate and rates of heat release are published in metric units, those quantities are given in metric dimensions (kilowatts and grams per second). FIREFORM includes seventeen different calculations. Most of these have been previously published and circulated from a separate computer package, also called FIREFORM [3]. The following are the major changes from the previous publication:

- a. Two additional procedures have been added.
  - (1) VENTILATION LIMIT - This program estimates the maximum amount of combustion that can be supported by the air drawn in through a room opening that is also the principal path for venting the products of a fire in that room.
  - (2) MASS FLOW THROUGH A VENT - This program estimates the mass and volumetric flow of fire products through an opening once a ventilation limited condition occurs. Specifically it estimates the mass and volume of hot gases exiting through the upper portion of the opening, the mass and volume of gas (assumed to be air at 70 °F (21 °C)) entering through the lower portion of the opening, and the position of the neutral plane in the opening.
- b. Two of the procedures reported in the initial FIREFORM [3] have been revised as follows:
  - (1) UPPER LAYER TEMPERATURE - The program UPPER LAYER TEMPERATURE has been revised to allow the user to input a time dependent description of a fire. The program then calculates the estimated upper layer temperature for the energy input and time exposure of each point on the input curve. The program has also been revised to estimate the point at which a ventilation limited condition occurs and the upper layer temperature that would be indicative of flashover. Finally, an additional procedure has been added to allow the user to estimate post flashover temperatures.
  - (2) PLUME FILLING RATE - This procedure has been revised to call for additional inputs from the user estimating the portion of energy lost from the plume.

- c. The input to the ASETBX ROOM MODEL, SPRINKLER DETECTOR RESPONSE, and UPPER LAYER TEMPERATURE have been revised to accept fire data files developed using MAKEFIRE.
- d. The user interface on all of the routines has been revised from the previous successions of prompts to more user friendly menus that present all or most of the required inputs in one screen and allow the user to revise inputs in any sequence he chooses.

#### 1.6 NATURE OF MAKEFIRE ROUTINES.

MAKEFIRE is a series of procedures for developing computer files describing the free burn combustion of one or several fuel packages. The files are then used as fire descriptions for the pre-flashover computation phase of FPETOOL. The same fire descriptions are also useful in a number of the routines in FIREFORM. The individual MAKEFIRE procedures are separately listed in the MAKEFIRE package selection menu.

#### 1.7 NATURE OF FIRE SIMULATOR.

FIRE SIMULATOR is an integrated set of equations (i.e. a model) designed to approximate conditions occurring in spaces, response of heat or smoke actuated devices in those spaces, and effluent (energy, gases, and fuel) from those spaces to other locations. Features include the following.

- a. Required input is in terms normally used in the practice of fire protection engineering, code enforcement, and related design.
- b. The interactive input routine allows the user to enter information by responding to questions or entering data in forms displayed on the computer screen.
- c. Once a case has been defined, it can be saved, reused, or altered and reused.
- d. Output is displayed on the screen, printed if desired, and loaded into an ASCII file suitable for further study and use with various graphing programs. Also, in cases where there is an opening between the fire room and the rest of the building, an additional file suitable for use as an input fire is produced. This file records the energy and potential fuel effluent from the fire room through that opening. This is intended as input for subsequent use of FIRE SIMULATOR to examine the exposed room or space.
- e. FIRE SIMULATOR operates in a single room fashion. It can, however, be successively used for a series of rooms provided that the subsequent rooms are of a reasonable size. FIRE SIMULATOR does not account for the impact of buildup of smoke and heat in a subsequent room on the development in the source room. Therefore, FIRE SIMULATOR becomes less dependable in a multiroom situation when the second room starts to develop a smoke layer that is at least as deep as the opening between the rooms and has temperatures suffi-

ciently close to those in the source room to significantly affect the free flow of smoke from the first room. Also, if the second room fills with a smoke (regardless of temperature) that has a reduced oxygen supply, the oxygen content in the flow into the source room will be affected. This impacts on the burning rate in the source room.

f. FIRE SIMULATOR can be applied room by room to cases within the following scope.

- (1) There is a room having ceiling and walls.
- (2) The room may be closed or open. FIRE SIMULATOR can account for two openings (one internal and one external.<sup>1</sup>) If the room is closed FIRE SIMULATOR assumes there is some leakage. FIRE SIMULATOR does not calculate pressure increase due to thermal expansion of gases. FIRE SIMULATOR assumes that leakage is sufficient so that such pressure increase is negligible in terms of the hazard development computed by FIRE SIMULATOR.
- (3) FIRE SIMULATOR can predict the response of one heat detector (or sprinkler head) and one smoke detector in each room.
- (4) FIRE SIMULATOR accounts for the impact of the materials used for room lining. It can divide the room lining surface (walls and ceiling) into up to three wall segments and three ceiling segments. Each segment may have a different surface material or thickness. Wall and ceiling materials are treated entirely on the basis of their thermophysical properties. Combustibility is not considered in this aspect. If the walls are combustible, the impact of the burning of the lining materials must be added to the fire input in the pre-flashover mode. In the post flashover mode FIRE SIMULATOR accounts for both the mass and energy release from combustible linings. In treating walls, FIRE SIMULATOR assumes that all of the wall materials run from floor to ceiling. At this time, it is unable to differentiate those materials (such as wainscoting) that are not full height.
- (5) FIRE SIMULATOR can be instructed to halt:
  - (a) At a given time,
  - (b) At a given time following the operation of a heat actuated device, and
  - (c) At a given time following the activation of a smoke detector. When so halted, the user can adjust the size of both the internal and external openings.

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<sup>1</sup>FIRE SIMULATOR develops a fire data file that tracks the flow of heat energy and unburned fuel through the inside opening. This allows the user to consider the developed fire data file as input energy to a fire in an adjacent room or space.



- (6) To operate FIRE SIMULATOR, it is necessary for the user to input a description of a free burn fire. This will be used by FIRE SIMULATOR in the pre-flashover phase. The user can do this either by using a file developed through MAKEFIRE or a previous run of FIRE SIMULATOR. Also the free burn fire description can be entered at the time of use as a series of data points.
- (7) If the smoke layer temperature reaches the level designated as flashover, FIRE SIMULATOR will halt. The user will then be queried regarding the total fire load in the space and factors relating to the exposed fuel surface area. From this data, FIRE SIMULATOR generates the post-flashover mass burning rate, the actual rate of heat release within the room, and the duration of the fire.

#### 1.8 OPERATIONAL PROCEDURE TO USE FPETOOL

FPETOOL is a program compiled in Quick Basic. The normally distributed version is the compiled version. The source codes are available from the Center for Fire Research.

The system is designed to operate on personal computers having the MSDOS 3.1 or higher operating system. FPETOOL is designed to operate whether or not a math coprocessor is present but operates faster if a coprocessor is present. FPETOOL is not copyrighted nor copy protected. Users are urged to make a backup copy. Transfer to others is at the user's discretion<sup>2</sup>.

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<sup>2</sup>After FPETOOL is installed on a computer, it creates one or more files having the extension .FPE. These files configure the internal search procedures within FPETOOL to the specific arrangement of the computer involved. Since most computers have unique arrangements of files and directories, files having the extension .FPE should not be transferred from one computer to another. To do so can cause FPETOOL to crash.

## 2. QUALITATIVE OVERVIEW OF PROCEDURES

### 2.1 ENGINEERING ROUTINES USED

As with any computer program, a large percentage of the computer program relates to inputs, outputs, and internal accounting. While important, these are not addressed in this document. Rather, this document addresses the engineering procedures and data sources involved. These are addressed individually for the procedures in FIREFORM and MAKEFIRE and the subroutines in FIRE SIMULATOR.

### 2.2 FIREFORM

FIREFORM consists of seventeen separate routines. Each of these routines perform an engineering computation. The routines and the relationships to data and computations are as follows.

#### a. ASETBX ROOM MODEL.

ASETBX is a simple mathematical model for estimating the rise in temperature and the descent of the fire produced hot gas layer in the room of fire origin. It considers conditions up to the point that the room approaches flashover but does not predict the conditions following the occurrence of flashover. ASET uses a simple point source entrainment and filling calculation that requires the user estimate the average portion of the energy produced by the fire that is lost from the flame or smoke layer. The form of ASET in FIREFORM has a fixed assumption that 35% of the energy in the flame is lost by radiation. The user is required however to enter a value representing the total heat loss fraction. The choice made has a major impact on the calculated temperature of the hot gas layer and a lesser impact on the calculated position of the bottom of that layer.

ASETBX addresses only one room (or other enclosed space) and assumes that there are no open doors or other vents to carry the hot gas layer from the room. ASETBX also assumes that there is some type of floor level vent sufficient to prevent any buildup of pressure due to the expansion of hot gases.

#### b. ATRIUM SMOKE TEMPERATURE.

This procedure, developed by Cooper [4], estimates the approximate average temperature in the smoke layer accumulated at the top of an atrium or other large space. The procedure is for steady state<sup>3</sup> fires only and should be considered to give only a broad estimation. The equation used is derived from the plume entrainment equation used in ASETBX and is considered valid only for those conditions where the temperature in the upper level is relatively low (approximately 220°F (104°C)). This limitation is important because the

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<sup>3</sup> For the purpose of this report a steady state fire is defined as one having a constant rate of heat release and/or a constant mass burning rate.

equation used does not consider heat transfer from the smoke layer to the surrounding walls. At higher temperatures, heat transfer would become a significant factor. The program provides an advisory informing the user of the maximum size of fire based on the clear height input entered.

#### c. BUOYANT GAS HEAD.

The equation in this procedure calculates pressure imposed by a column of gas that is at a higher temperature than the surrounding atmosphere. The equation as programmed assumes that the temperature in the surrounding atmosphere is 70°F (21°C). The equation used is directly extracted from the manual "Design of Smoke Control Systems in Buildings," by Klote and Fothergill [5]. A key assumption in this equation is that the smoke temperature is the same from the bottom of the smoke layer to the point of interest within that smoke layer. The pressure differential provided is the difference between that point in the smoke layer and a point in an adjacent column of gas that is 70°F (21°C).

#### d. CEILING JET TEMPERATURE.

This equation calculates the ceiling jet temperature flowing under a ceiling at a point outside the plume impingement zone. The equation applies to points on the ceiling that are separated from the point of plume impact directly above the fire by at least 0.2 times the height of that plume. The equation used was published by Alpert and Ward [6]. It is intended for estimating the likelihood of ignition of combustible materials or other heat incurred damage to ceiling level. As such, the constants used produce a conservatively high temperature as compared to similar calculations used for estimating the response of thermal detectors. For this reason, this calculation is suggested for estimating hazard but not for estimating the response of heat actuated safety devices. It is felt that the procedure entitled, "SPRINKLER/DETECTOR RESPONSE" or the more detailed procedures in FIRE SIMULATOR are more appropriate for detector response estimates. The procedure will adjust the temperature of the gas to recognize the change of entrainment if the fire source is located against a wall or in a corner. It also recognizes that any hot gas layer building up beneath the ceiling will change the predicted temperatures. To warn the user of this, the procedure reports the approximate time when this rise might start.

#### e. CEILING PLUME TEMPERATURE.

This procedure is a companion to the previous procedure "CEILING JET TEMPERATURE." It provides a means of estimating the near ceiling gas temperatures above a free burning fire. It can also be used for estimating the temperatures at other points in a fire plume provided that the point of interest is above the top of the estimated flame height. The equation is also extracted from the publication of Alpert and Ward [6] and operates in the same manner. This procedure is considered reasonable up to a point on the ceiling where the radial distance from the center line of the plume is not greater than 0.2 times the distance from the fire to the ceiling.

#### f. EGRESS TIME.

This procedure contains several related equations for estimating the time needed for a group of people to exit a given space or building. The approach is very general in nature and involves assumptions that need to be considered in its use. The critical assumptions are as follows.

- (1) Any congestion will occur at doorways or in stairways. Flow through horizontal routes to the stairways or exit doors are assumed to be relatively free flowing. This procedure is therefore inappropriate for theaters or other places of assembly where aisles or corridor congestion is expected.
- (2) Doors act as turnstiles that meter flow to about one person per second per door. This rate is considered to be approximately correct for doors between 34 and 36 inches wide. It is not expected that the rate would increase appreciably for wider doors. Where narrower doors are involved in the exit path, it is likely that the flow through doors will be less than that predicted.
- (3) The capacity of stairs is equal to approximately 1.83 persons per minute per foot of effective total stair width. The effective width of each stair involved is the tread width less twelve inches. The basis for this is the work of Pauls covered in the NFPA 101M, Alternative Approaches to Life Safety, 1988 [1].
- (4) Within a reasonable range of variation, the impact of stair steepness to exit flow is inversely proportional to the square root of the tread to riser ratio. This conclusion was developed through review of the data in NFPA 101M [1].
- (5) The rate of emergency flow is 250 ft. per minute on level travel and 40 vertical ft. per minute on stairs. Both of these values assume free flow. If significant congestion were to occur, these values would have to be revised for that portion of the egress path where the congestion occurs. The program provides the user the opportunity to adjust these flow rates if desired.
- (6) The procedure assumes 100% efficiency on the part of all persons involved in the egress. It assumes all persons start egress at the time the program assumes as zero time. Egress time also assumes that there are no interruptions to ideal (hydraulic) flow during the course of the evacuation. Such is seldom, if ever, true in actual practice and users should consider the additional impact of delays and interruptions in making safety estimates based on the calculations performed by this program.

NOTE: The values in items (2), (3), and (5), above, are adjustable by the user.

#### g. FIRE/WIND/STACK FORCES ON A DOOR.

This procedure contains equations for estimating the forces imposed on a door by a pressure resulting from the buoyant force of a fire. The procedure can also estimate the additional force that can be produced by wind and stack

effect. The equations used are derived from equations presented in the ASHRAE Manual, "Design of Smoke Control Systems in Buildings," by Klote and Fothergill [5]. The procedure involves the following assumptions.

(a) None of the forces being measured are constrained by a tight building or other situations that would constrict gas flow or development of the full theoretical force predicted by the equation.

(b) All forces are additive. This is a conservative assumption representing a "worst case" situation.

(c) The fire gases impacting on the door being evaluated are at a single temperature across the full extent of the portion of door covered by fire gases.

(d) Wind impacts on the building with a pressure coefficient as described by Klote and Fothergill [5] of 0.8. Also, there are broken windows or other means whereby the full impact of the wind is imposed on the door being considered in a manner additive to the vector of the force imposed by the fire.

(e) When considering stack effect, the neutral plane of the building is at a point three quarters the height of the building above grade. This is used as a reasonably conservative case for winter conditions. If the user desires to assume a different location, this can be accomplished by adjusting the height of the building so that the distance from the point being considered to the neutral plane is three quarters of the building height.

(f) The normal room temperature within the building is 70°F (21°C).

With these assumptions, this procedure uses simple vector force calculations. The force is calculated on the basis of buoyancy and wind forces as derived from Klote and Fothergill [5].

#### h. MASS FLOW THROUGH A VENT.

This procedure uses an iteration process to derive an approximate solution to the mass and volume flow out of the fire room, the mass and volume flow of air into the fire room, and the point of the neutral plane in an opening. The specific procedure used is derived from Kawagoe and as reported by Lawson and Quintiere in "Slide Rule Estimates of Fire Growth" [7]. The key assumptions are the following.

(1) The space in the room being vented is at a uniform temperature indicative of flashover or is in a ventilation limited condition. This procedure is inappropriate for that early stage of the fire when the increasing expansion of gases in the room causes all flow to be out of the room.

(2) There is either only one such opening in the space or all of the openings are at reasonably the same level in the space.

#### i. LATERAL FLAME SPREAD.

This procedure contains an equation for estimating the lateral speed of a fire spreading in a direction other than that impinged by flame from the burning material. Generally, this means lateral or downward spread from a vertical flame. This procedure is inappropriate for estimating the spread of fire proceeding in the same direction as the flow of gases from the source fire. Lateral flame spread is highly dependent on temperature of the unburned surface. The procedures used in this program were developed by Quintiere and Harkleroad [8]. The material properties required by this equation are derived using a test method described in the same reference. The values in this test method include a flame heating factor ( $\phi$ ), a derived value of thermal inertia ( $k\rho c$ ), and the ignition temperature of the material. In using this procedure, it is important that the data be derived from the test described by Quintiere and Harkleroad [8] or from a similar testing arrangement. It is felt essential that the data for  $\phi$  and  $k\rho c$  be derived from a single test. Users should note that the values derived from the referenced test for  $k\rho c$  are not the classic room temperature values for the material properties involved. The procedure provides a brief table extracted from the referenced report of values representing a number of lining materials.

#### j. LAW'S SEVERITY CORRELATION.

This procedure contains an equation for estimating the equivalent fire severity (duration) of the burnout of all of the available fuel in a room with at least one opening. The correlation was developed by Law [9]. The results predict the potential impact of a post flashover fire in terms of equivalent exposure to a fire endurance furnace following the European equivalent of the standard time-temperature curve.

Law based her correlation on data developed through an international research program carried out under the auspice of the Conseil International du Batiment (CIB). The results of this effort are reported by Thomas and Heselden [10]. All of the tests were conducted with wood crib fuel sources. Law reports a 20% variation depending on the porosity of the fuel. In wood cribs, porosity is based on the ratio of openings between the sticks of the crib to the space filled by these sticks. The greater severity is expected with more loosely packed cribs.

In contrast to interior finish fires, for the burning of wood cribs the majority of the combustion usually takes place within the fire room and a relatively small amount of unburned fuel leaves in the fire gases. It is expected that there are many fire conditions where either the large surface area of ordinary fuels or the presence of some types of plastics will result in the production of fuel at a much faster rate than oxygen can enter to burn that fuel. Where this occurs, a significant quantity of unburned fuel can be vented from the fire room. Were oxygen immediately available, this would be expected to appear as a large flame at the opening. If this is the case, this procedure is likely to over-predict the fire duration.

This correlation is also not appropriate for rooms that do not have openings for ventilation. While no precise minimum can be stated, it is suggested that this procedure not be used unless the size of the opening is at least 4 sq. ft. (0.4 square meter).

#### k. PLUME FILLING RATE.

This procedure predicts the volume flow of smoke and companion gases in a plume at a point above the fire. The equation used is abstracted from ASETBX [11] and adjusted by Stroup [12] for a constant rate of heat release. It is considered reasonable for estimating the gas flow rates in those portions of the fire plume above the flame. The volume of hot gases includes the air entrained in the fire plume. This procedure is not recommended for conditions in or near the flame itself.

#### 1. RADIANT IGNITION OF A NEAR FUEL.

This computation predicts the approximate energy level that a free burning exposure fire must have to ignite a nearby item, provided the exposed fuel is not so close as to be touched by the flame of the burning item. The calculation also assumes that the exposed fuel item is too close to consider the burning item as a point source. Rather, the exposed fuel sees the broad side of a fire typical of that produced by a free standing upholstered chair or couch. The relationships involved in this computation were developed empirically from tests and reported by Babrauskas [13]. The data reported by Babrauskas has been converted to an algorithm contained in this computation. The results should be considered a simplistic estimation based on a limited set of data and assumptions regarding the susceptibility of exposed material. The procedure divides all exposed materials into three classes on the basis of the level of energy present at the moment of ignition. The three classes, suggested by Babrauskas, are as follows.

(1) Fuel is easily ignited - material expected to ignite when the incident energy on it is  $10 \text{ kW/m}^2$ . This is typical of thin materials such as curtains or draperies.

(2) Fuel is normally resistant to ignition - material expected to be ignited when the incident energy is approximately  $20 \text{ kW/m}^2$ . This is considered appropriate for upholstered furniture and other material that has some mass but only a moderate heat sink.

(3) Fuel is difficult to ignite - approximately  $40 \text{ kW/m}^2$  required to ignite the exposed fuel. This is typified by combustible materials that contain reasonable heat sink capacity, such as wood that is at least 1/2 inch (0.013 m) thick.

Other approaches to developing the likelihood of an exposed material to ignition are included in the procedure entitled FREEBURN in MAKEFIRE.

#### m. SMOKE FLOW THROUGH AN OPENING.

This procedure contains an equation for estimating the volumetric flow of heated smoke through an orifice type opening. The equation is designed for openings ranging from cracks around doors to openings as large as door openings. The equation is inappropriate for openings having duct like features (i.e., a passage where the passage length is significantly greater than the narrow dimension of the opening).

The equation calculates flow based on the pressure produced by the hot gas layer developed by a fire. The equation computes this pressure based on the average temperature of the hot gas layer and the height of the opening above the base of that layer. It does not calculate the pressure produced by other pressure sources such as wind pressure or stack effect. It also assumes that the space has sufficient venting so that there is no increase in pressure other than that produced by the reduction in density due to the expansion of hot gases. As programmed, the equation assumes that room temperature is 70°F (21°C). This equation is derived from those presented by Klotz and Fothergill [5] in the ASHRAE Manual, "Design of Smoke Control Systems for Buildings." It uses standard orifice equations and coefficients appropriate for simple building openings.

#### n. SPRINKLER/DETECTOR RESPONSE.

This procedure contains a method for calculating the thermal response of a detector or sprinkler head located near the ceiling of a large space. The basic equations in this procedure are separately distributed on a program developed by Evans and Stroup entitled DETACT-QS [14]. The equations are based on the correlations by Alpert [15]. The theory and documentation are presented by Evans [16]. The program is a quasi steady state procedure.

The program assumes an unconfined ceiling (the case for a large room) and a detector or sprinkler head positioned in the hottest portion of the fire induced gas jet under the ceiling. In a room small enough to have a significant hot gas layer condition prior to detector (or sprinkler head operation), this program will indicate an activation time that is longer than that which would actually occur. FIRE SIMULATOR includes procedures for estimating the impact of the hot gas layer and would be the preferred procedure where the impact of such a hot gas layer is an important factor.

This program can also indicate an unrealistically fast activation of sprinkler heads or detectors located on a wall or on the ceiling close to the wall. This is due to back pressure restricting the flow of hot gases to the ceiling - wall corner space. An approximation can be made to the correct detection device activation by revising the program to reduce the ceiling jet velocity. While the SPRINKLER/DETECTOR RESPONSE procedure in FIREFORM cannot adjust for such a condition FIRE SIMULATOR includes that capability.



#### o. THOMAS' FLASHOVER CORRELATION.

This procedure contains an equation for estimating the amount of energy necessary in a room or similar confined space to raise the upper layer temperature to a point likely to produce flashover. The equation used was developed by Thomas [17]. The correlations used by Thomas were derived from steady state fires in test rooms constructed of concrete materials. Time has demonstrated this correlation to be robust and that it can handle a wide range of conditions producing estimates normally within about twenty percent of the values observed in tests or derived by other more elaborate procedures.

#### p. UPPER LAYER TEMPERATURE.

This procedure estimates the upper layer temperature developed by a steady state or growing fire in a vented room. A vented room is one having a door or window to provide air to support combustion and a path for venting combustion gases. The equations used have been published by Quintiere [18] and consider the dimensions and the thermal characteristics of the lining material of the room. The program assumes thermally thick walls. It is therefore inappropriate for use on rooms with thermally thin walls. A prime example of such being uninsulated metal walls. The procedure will also not work on a room that is not vented. It is also considered ill-advised to use this program on rooms where the size of the opening is very small as compared to the surface area of the room. For example, it would be inappropriate to use this procedure for estimating the temperature buildup in a closed room with the only opening being a crack between the door and its frame. ASET or FIRE SIMULATOR would be better procedures for such a case.

The program also can estimate post flashover temperatures, again using the equations proposed by Quintiere [18]. The post flashover temperature is based on the room opening and heat losses to the wall. It assumes that the mass burning rate is sufficient to produce a ventilation limited case. For very large openings, the equation used for estimating post flashover temperatures can predict impossibly high temperatures. When predicting post flashover temperatures, the user must recognize this. The program reports the burning rate that would be needed to support the indicated temperature and raises a warning flag if that temperature exceeds 2500°F (1371°C).

#### q. VENTILATION LIMIT.

This procedure provides an equation for estimating the maximum burning rate that can take place within a room that has an opening. The calculation assumes 100% combustion efficiency for the air entering the room through the opening. If the rate at which the fuel source is losing mass (burning) is less than the ventilation limit, the fire is considered to be "free burning." If the mass loss rate is greater than the ventilation limit, the excess fuel will flow from the room as flame if there is oxygen available outside the room and the burning is considered ventilation limited. The equation used is derived from the pioneering work of Kawagoe [19] and has been examined and used by many others. The ventilation limit is calculated independently for each opening but assumes that all openings are essentially at the same level. It is inappropriate to use this calculation in any situation where the

openings are at widely different levels. Where the various openings however are essentially at the same level (reasonably appropriate for a space having ordinary windows and doors on the same floor) the ventilation limit for a space is approximately the sum of the ventilation limits for all openings into that space. This assumes that all such openings have access to unrestricted fresh air.

## 2. MAKEFIRE

MAKEFIRE consists of five separate routines. Only two perform computations. The routines and their relationships to data and computation are as follows.

### a. LOOK.

There are no computations or data in this routine. It allows the user to review any fire data files that are currently available. LOOK provides assistance in evaluating the catalog of fire data files available to the user.

### b. RATES.

There are no computations in this routine. It contains a listing of estimated peak and growth rates of the free burn of selected fuel packages. This list was assembled by Nelson [20].

### c. MYFIRE.

This routine contains neither computations nor data. It provides an opportunity for the user to make a fire data file by entering a series of fire data points. It is arranged to allow the user to enter data in terms of either rate of energy release or rate of mass loss. The user may also select English or metric units for the input. The files created are always in metric units (seconds, kilowatts, and grams per second.)

### d. FORMULA.

This file creates fire data files based on the use of power law or exponential growth equations as selected by the user. The equations are presented in Chapter 4. FORMULA allows the user to specify the criteria for growth, steady, and decay phases of free burn and the criteria for transition from one to the other. The user can select English or metric units. The fire data files created by FORMULA are in metric units.

### d. FREEBURN.

This program combines the impact of several fuel packages (previously described as fire data files) into a single output fire. In addition to the selected fire data files, FREEBURN considers the physical separation between the fuel packages, the radiant fraction expected from their burning, and their surface area. The functional procedure is as follows.

(1) FREEBURN can handle up to five separate fuel packages. The spacings between fuel packages, the dimensions of the burning surfaces, and the radiant fractions from the flames produced are prescribed by the user.

Note: FREEBURN assumes a radiant fraction of 0.35 unless changed by the user.

(2) The user identifies up to five fuel packages to be evaluated, the separation between the fuel packages, the area of each fuel package, and ignition suitability data for each fuel package. The user also identifies one or more fuel packages as ignited at the start.

(3) Based on the rate of heat release defined by the fire data files representing each ignited fuel package, the program calculates the radiant emission from each burning package. This is a function of the rate of heat release prescribed by the fire data file multiplied by the radiant fraction prescribed by the user.

(4) The radiant energy transfer from each burning fuel package to each unignited fuel package is calculated using approximations proposed by Modak [21]. Both the point source approach proposed by Modak and his adjustments for situations where proximity between the source and the target invalidate direct application of point source concepts are used. In this calculation, it is necessary to identify the center of the fire. To do this, the program arbitrarily assumes a circular fire with one edge at the point identified by the user as the separation between the ignited fuel and the unignited target being evaluated. The diameter necessary to produce an area to generate the rate of heat release is based on a user adjustable default value of 100 BTU/sec/ft<sup>2</sup> burning area (1079.3 kW/m<sup>2</sup>). (The routine RATES provides information of expected heat release rates of a number of fuel assemblies.) Further, the calculation assumes that the distance from the edge of the fuel to the effective radiant center does not increase once the fire is more than about 3.28 ft. (1m) in diameter. An additional reduction in radiant emission is included to recognize the low emissivity in the initial stages of burning when the flame is small and thin. The actual radiative emission from the flame is considered to grow linearly from zero to the prescribed radiant fraction between fire initiation and the achievement of a steady radiant fraction.

(5) Using the combination of calculated radiant flux and Modak's radiant transmission equations the impact from each ignited fuel on each unignited fuel is calculated. The program assumes that all of these impacts are normal to the exposed fuel and impact at the same point. The impacts are therefore considered cumulative and summed.

(6) The user may select to determine the ignition based on a critical incident flux, a critical ignition temperature, or a preset time.

(a) If either the critical incident flux or time of ignition approach is used, the program will run much faster. Critical flux is a factor chosen by the user. The program provides some

guidance in this based on suggestions derived from the work of Babrauskas [13]. If a fixed time is used, the program will cause ignition of the designated fuel package at the specified time and report the incident radiant flux on that fuel package at that time.

(b) If ignition is based on achievement of critical ignition temperature, a successive integration approach is used to approximate the rise in surface temperature of the target. This approach is based on the experimental correlations of Quintiere and Harkelroad [8]. This method approximates the rise in temperature as a function of incident energy, thermal diffusivity and specific heat. The approach involves successive integration and assumes thermally thick material. Computationally, the approach is quite slow. This is particularly so when the time to ignition is long. Long time to ignition can result when the target material has a high ignition temperature, the target material has thermal physical properties that resist heating, or the exposing fire imposes a low incident energy on the target material. The critical ignition approach is based, however, on calculated heat transfer rather than assumed critical values. When used it reports the calculated surface temperature, time of ignition, and incident flux at that time. Users will have to assemble data on thermal inertia and ignition temperature to use this feature. Since the computation is an extension of the correlations from test data, the needed properties are best derived from these data.

### 3. FIRE SIMULATOR

FIRE SIMULATOR involves a series of separate computations assembled to address a single problem. The discussion of the methods used is broken down by computational modules.

#### a. Core Model.

The heart of FIRE SIMULATOR is a room compartment fire model. This model uses the computational procedure developed by Zukoski [23], then used by Cooper and Stroup as the basis for their model, Available Safe Egress Time (ASET) [24]. Later their work was reprogrammed with a different solver routine in a BASIC format by Walton as ASETB [11]. FIRE SIMULATOR uses the computation format developed by Walton for ASETB. In FIRE SIMULATOR, the basic computation routine of ASETB has not been changed. However, a number of subsidiary routines using the values developed by ASETB and internal adjustments to calculate inputs needed by ASETB have been added.

#### b. ASET Approach.

The ASET model calculates the impact on a room environment of a time varying rate of heat release. In ASETB the details of the time varying rate of heat release is input provided by the user. As used in FIRE SIMULATOR, ASET marches through time in one-second intervals. ASET uses the concepts of

conservation of energy and conservation of mass to compute the temperature and volume of the smoke layer produced by the prescribed rate of heat release.

ASET deducts a portion of the energy input to account for that lost by direct flame radiation. In FIRE SIMULATOR, this loss is considered to be 35% but can be reset to a different value by the user.

The remaining energy is reduced by a factor accounting for other heat losses. In the standard ASET model, this is a user input. In FIRE SIMULATOR, it is internally calculated. In order for FIRE SIMULATOR to make the calculations involved the user provides input data on the walls and ceiling materials. The user is provided with a menu of typical materials to select or revise to fit the need.

The rise in temperature is then based on the remaining energy. This produces a predicted temperature rise in the smoke layer. In the process, ASET also calculates the fuel mass released and the air entrained in the rising plume. These are used to calculate the mass, density and thickness of the upper layer.

The resulting reduction in clear height above the base of the fire causes a change in the height between the fire source and the interface. One result is a shorter distance for entrainment of clear air. Both the amount of entrained air and the temperature are strongly related to the clear height for entrainment. Therefore, the filling rate of the space decreases as the smoke layer approaches the fire. Also, the temperature of the gas entering the upper layer increases as the amount of cooling, clean entrainment air decreases.

ASET as originally developed involves two simultaneous differential equations in making the above computation. These continue to be the computational heart of FIRE SIMULATOR.

One equation calculates the increase in temperature considering the energy input (partially prescribed by the user and partially calculated by the program), the energy losses (prescribed by the user), and the air entrained by the rising plume (calculated by the program).

The other calculates the rate of descent of the smoke layer as a function of the increase in temperature and the rate of mass flow in the rising plume at the point where it meets the descending smoke layer. The rate of mass flow is a combined function of the prescribed rate of energy input less the prescribed radiation loss from the plume and the distance from the surface of the burning fuel package to the bottom of the smoke layer.

#### c. FIRE SIMULATOR Adjustment for Door or Other Opening

The basic ASET routine is designed for a room without any openings. FIRE SIMULATOR is arranged to include an opening at the option of the user. Where a door opening exists, a four step procedure is involved.

(1) Where the height of the smoke layer is equal to or greater than the top of the door, the normal ASET calculations are used.

(2) Initially after the smoke level has descended below the top of the door, the flow through the smoke filled portion of the door opening is considered as a simple weir. During this phase, the out-flow is based on the smoke flow calculation equation for a vertical opening in FIREFORM.

(3) A maximum smoke depth in the opening based on the temperature in the smoke layer has been established as a result of sensitivity analysis conducted using FIREFORM program MASS FLOW THROUGH A VENT. From this analysis FIRE SIMULATOR sets the minimum clear heights from the sill of the opening to the smoke layer at 39% to 49% of the opening height depending on smoke temperature. The higher the temperature, the lower the interface. If the flow through the door using the weir flow approach exceeds this level, the program limits the interface in the opening to the calculated minimum clear height. Other factors in the program also limit the maximum rate of heat release in the room to that which can be supported by the air drawn into the room through the restricted opening (See paragraph e, below.) The smoke level in the room is, however, allowed to continue to descend as dictated by the smoke filling calculations derived by the ASET based equations less the vented mass.

(4) Enthalpy flow through the opening is calculated based on the mass and temperature of out-flowing gases. That energy is then deducted from the total energy in the smoke layer.

#### d. Calculation of Heat Loss Factors

Since FIRE SIMULATOR is based on the ASET model it is necessary to calculate a value referred to as "heat loss factor." The heat loss factor represents the proportion of the heat energy released by the fire that is lost in terms of heating the upper layer by either radiation from the flame or by heat transfer to the room surfaces. It does not include any heat losses resulting from mass transfer of hot gases out of the room. Those losses are separately calculated. Heat loss factor is discussed, herein, in terms of the fraction of the heat produced that is lost. A heat loss factor of 0.8 means that 80% of the heat produced is lost through radiation from the flame and heat transfer to the room surfaces.

FIRE SIMULATOR calculates heat losses from the smoke layer to the ceiling and those portions of the wall in contact with the smoke layer. The heat transfer to the walls and the portion of the ceiling in contact with the smoke layer is developed using the effective transfer coefficient calculation method contained in the room temperature estimation procedure developed by McCaffrey, Quintiere, and Harkleroad [25]. This approach calculates an effective heat transfer coefficient per unit area for individual materials. Two regimes of heat transfer are involved.

The first regime addresses the initial stages of heating. It considers the impact of thermal inertia. It lasts a time estimated to be equivalent to the time required for a heat pulse to travel from the exposed to the unexposed face of the lining material. During this period the effective heat transfer coefficient varies inversely with the square root of time of fire exposure.

The duration of this regime is a function of the thermal physical properties ( $k\rho c$ ) and thickness of the material involved.

The second regime starts when the program (using the procedures established by McCaffrey, et. al [26]) determines that a heat pulse has penetrated the thickness of the surface material. From this point on the effective heat transfer coefficient is constant. It is a function of the thermal conductivity ( $k$ ) and thickness of the material.

The surface temperature of the exposed materials is then calculated using a simplified approach suggested by Quintiere [27]. This approach assumes that the temperature of the space on the unexposed side of the lining material stays at room temperature. The actual loss of energy is based on the effective heat transfer coefficient, the temperature differential between the smoke temperature and surface temperature of the lining materials, the resulting heat loss per unit area and the area of the smoke in contact with the lining material.

In addition, the estimated radiant heat loss from the boundaries of the smoke layer is calculated. In the pre-flashover mode, the size of the radiator is set equal to twice the ceiling area and all of the wall area in contact with smoke (i.e. the total boundary of the smoke volume.) In calculating radiant energy losses, the wall and ceiling surfaces temperatures are set at the calculated temperatures; the floor is at the pre-fire room temperature. In the pre-flashover mode no consideration is given to the effect of any burning surfaces on estimated radiant heat loss. This tacitly assumes that the area of burning surface is small as compared to the total surface area of the room.

FIRE SIMULATOR requires that the user enter data describing the extent of burning surfaces if the program is to proceed into the post flashover mode. In calculating the heat loss factor, FIRE SIMULATOR assumes that no heat is transferred from the smoke layer to any burning surface. Therefore, as the amount of room surface that is burning increases, the amount of heat loss decreases.

The sum of these losses and the radiant loss from the flame are totaled and compared to the input energy. This is converted to a proportion of the total input energy to provide the heat loss factor required by the computational approach of the ASET model.

Limits are set on the maximum heat loss factor. The defaults for these values are listed in the program. The user may change any value if so desired.

In addition, in any case where FIRE SIMULATOR calculates a smoke level temperature in excess of 572°F (300°C) the maximum heat loss factor value is limited to 0.8.

The user is also provided with the opportunity to adjust the maximum heat loss factor in rooms where the room area is large as compared to the distance from the fire to the ceiling. Such an adjustment is necessary because the ASET assumption of even temperature distributions throughout the smoke layer and across the exposed wall surfaces seriously breaks down in such spaces. An

approximate compensation can be made by setting an arbitrary maximum value for the heat loss factor. Cooper and Stroup [24] gives limited information on this. His information is included in a prompt which will appear at any time when the ratio of the square root of the room area to distance from the ceiling is greater than four. Users should understand that the FIRE SIMULATOR is less likely to produce accurate results in large spaces with low ceilings because of this. It is hoped that a more sound approach may be available in the near future.

Finally, the minimum heat transfer factor value is set at 0.6 as recommended by Cooper and Stroup [24].

#### e. Revisions to Rate of Energy Release

Where there are no room openings, the amount of combustion that can occur is based on the amount of oxygen available from the air in the room plus that in any air supplied by mechanical systems. (At the present time FIRE SIMULATOR does not handle air that may be available through peripheral leakage.) Where there are room openings, the amount of air that can be drawn into the fire room through those openings is calculated and added to the supply available from the air in the room and any mechanical air supply systems.

The oxygen available in the room at any time is determined by adding the oxygen content in the smoke layer as calculated by FIRE SIMULATOR to an assumed 23% oxygen mass (i.e. 21% volume percent) in the volume below the smoke layer. Each gram of oxygen is considered capable of supporting the release of 13 kJ of heat energy as described by Huggett [27].

The potential for support of combustion by the oxygen content of the air drawn into the room through room openings is similarly based on the ability of air to support 13 kJ of energy release per gram of oxygen in that air. The maximum amount of such air is calculated using the algorithm for calculating ventilation limit contained in FIREFORM. This is derived from the relationships originally developed by Kawagoe [19]. The mass flow rate through the opening is considered to be a function of the area of the opening times the square root of its height.

Where the rate of energy release from the input fire in the pre-flashover mode or from the calculated fire in the post-flashover mode exceeds the available oxygen, the rate of heat release is reduced to that supported by the incoming air. Any additional energy indicated by the calculated rate of energy release from the prescribed input fire is considered unburned fuel and handled as such.

The oxygen concentration calculated for the smoke layer is continuously monitored by FIRE SIMULATOR. The oxygen content needed to support combustion in the smoke layer is considered to be a function of the smoke temperature, starting at about 10% oxygen at room temperature and approaching 2% oxygen as the temperature rises to and above the flashover range. (These limiting oxygen concentrations can be adjusted by the user.) If the oxygen content in the smoke drops below the oxygen concentration considered necessary to continue combustion in the smoke layer then burning is limited to that



supportable by air entrained in the portion of the fire plume below the smoke layer. This involves the following appraisals.

### (1) Oxygen in Smoke Layer.

The oxygen consumption relationship reported by Huggett [27] is used. It has been established that the combustion of common fuels consumes about 0.076 grams of oxygen for each kJ of energy produced (i.e. about 13 kJ of energy per gram of oxygen consumed.) Using this relationship, FIRE SIMULATOR keeps track of the oxygen consumption, the oxygen concentration in the smoke layer, and the total oxygen available for combustion.

### (2) Oxygen required for combustion.

FIRE SIMULATOR assumes that there must be a minimum oxygen content in the primary air drawn into the fire plume. A default value of 10% oxygen content, adjustable by the user, is set. This limiting value is mandated for conditions where the smoke level descends over the fire source. When the smoke layer is above the level of the fire, FIRE SIMULATOR assumes that the air below that level contains 21% oxygen. When the air entrained below the smoke level is sufficient for total combustion of the fuel being produced by the fire, FIRE SIMULATOR assumes that all of the potential energy in that fuel is released within the room.

When the smoke layer is above the fuel source and the oxygen content of the air entrained below the smoke layer is not sufficient for full combustion, FIRE SIMULATOR determines if the oxygen in the smoke level is sufficient to complete the combustion process. The oxygen needed to burn fuel gases in a reduced oxygen atmosphere is considered by FIRE SIMULATOR to be a function of the temperature of the atmosphere involved, as stated above. For lack of a better basis, FIRE SIMULATOR uses a linear relationship to estimate the oxygen needed at smoke layer temperatures between room temperature and flashover temperature. The default values are set at 10% at room temperature and 2% at flashover temperature. Both are adjustable by the user. If the level of supportable combustion drops below 0.1 kW FIRE SIMULATOR terminates further calculation and ends the run.

FIRE SIMULATOR assumes that the mixing of fuel and air in post flashover burning involves turbulence not present in the preflashover regime. This turbulence is held to continue as long as the available fuel exceeds the combustion ability of the available air (i.e. ventilation limited burning<sup>4</sup>.) During such burning FIRE SIMULATOR assumes that the normal plume relationships no longer hold and that all available air burns. If the relationship returns to a fuel controlled burning regime FIRE SIMULATOR reverts to prior rules for determining the potential of burning fuel in the smoke layer.

### (3) Flame Length.

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<sup>4</sup>See paragraph 2.a. of chapter 5 for discussion of ventilation limit and ventilation limited burning.

The relationships for air entrainment into a fire plume developed by Heskestad [28] are used in FIRE SIMULATOR. This approach uses two separate equations depending on the relationship of the smoke layer to the flame. Use of this approach requires determination of the flame height. Heskestad's equations from the same reference are used to calculate flame height. Flame height in this case is an estimate of the point where the flame tip is present about 50% of the time. This is also considered as the point in the plume where the temperature rise is approximately 500°C (900°F). Given an initial room temperature of 70°F (21 C) this equates to an actual fire plume temperature of about 970°F (521°C). Flame length is dependent on both the rate of heat release from the burning fuel and the size of the fire bed. Heskestad's equation for pool fires [28] is used. The pool fire approximation is used because of the sparsity of information on flame lengths above other types of fire. The pool fire assumption is believed to be a reasonable approximation for fires on common furniture items. It is less reasonable for fires involving extensive vertical combustible surfaces (e.g. combustible walls), ceiling fires, or fires that can quickly involve large surfaces within the fuel package (e.g. palletized storage.) If FIRE SIMULATOR determines that a portion of the fuel generated cannot burn within the involved room, the reporting of flame height is terminated. This, because the calculation of fire bed size is no longer meaningful.

#### (4) Effective Diameter of Fire Source.

Both the flame length equation and the equation used for air entrainment into the rising plume prescribed by Heskestad [28] involve the concept of virtual source. The concept of a virtual source is a computational tool rather than an actual physical entity. The virtual source of a fire is that point in space where a fire releasing the energy evolved at that moment would result in plume conditions identical to those actually produced. The virtual source calculation is a function of both the rate of heat release and the diameter of the fuel bed.

The equation used for flame height approximates the fire as a circular source having the same area as the fire bed. If the area of the burning combustibles is known, the user may input this area and FIRE SIMULATOR will use it as the maximum possible area. If not, the maximum possible area is considered to be the entire area of the room. Within this limit, the burning area is assumed to be a function of the rate of heat release. To make this approximation, the program assumes that the fire is producing approximately the same rate of heat release per unit area of burning material.

#### (5) Fire Plume Temperature.

The purpose of a separate calculation of entrainment is to determine if there is sufficient air to assure combustion should the flame penetrate the upper layer. Therefore, only those calculations related to entrainment in the portion of the plume roughly at or below the theoretical flame height are considered. In this range, there are two regimes of entrainment.

Near the base of the plume where the flame is a constant mass of steady combustion, the entrainment rate is nearly linear with the height above the

actual flame bed. Above that point, where flame is intermittent, entrainment increases dramatically and the entrainment varies by a factor close to the  $5/3$  power of the change in distance above the virtual source. The point of demarcation between these two regimes has been estimated by Heskestad as the point where the center line plume temperature has increased about  $500^{\circ}\text{C}$  (for an initial room temperature of  $70^{\circ}\text{F}$  ( $21^{\circ}\text{C}$ ), this produces a center line plume temperature of about  $970^{\circ}\text{F}$ , ( $521^{\circ}\text{C}$ ).

Using these relationships, the program determines the entrained air in that portion of the plume below the smoke layer. Since each gram of oxygen in that air can support combustion producing approximately 13 kJ of energy, a value of the maximum supportable burning rate resulting from the air entrained below the smoke level can be established. If the oxygen in the smoke layer has been reduced below the level necessary for complete combustion in the smoke layer and the rate of available fuel exceeds the potential of the entrained air, the amount of combustion that can be produced by the entrained air is set as the limit of combustion within the room.

The above limit is compared to the limit of combustion that can occur as a result of air drawn in through room openings and provided by HVAC systems. Whichever of these two is lesser governs. Fuel production that exceeds this amount is considered by FIRE SIMULATOR to be unburned fuel. If there are openings in the room, this unburned fuel is accounted for in the effluent discharged through these openings. If the room has no openings, this excess fuel is considered to be stored as unburned fuel gases in the smoke layer.

#### f. Handling Reduction in Oxygen in Primary Combustion Air

If the smoke layer descends to or below the top of the fuel and the oxygen content in that layer is less than a preset value (default value is 10%, adjustable by user) the program terminates if the condition continues for more than 5 seconds. The 5 second delay is included to avoid stopping the program due to momentary instabilities within the numerical calculation within FIRE SIMULATOR rather than a recognition of an element of the physics of fire. In such case the following message appears on the screen. "THE DROP OF THE SMOKE LAYER TO COVER THE BURNING MATERIAL ALONG WITH REDUCTION OF OXYGEN IN THE SMOKE LAYER TO BELOW 10% PRECLUDES NORMAL BURNING. THE FIRE MAY GO OUT OR MAY CONTINUE BURNING AT A REDUCED BURNING RATE. THAT RATE BEING DETERMINED BY FACTORS NOT PREDICTABLE BY THIS PROGRAM" FIRE SIMULATOR stops further computation in such case.

#### g. Handling Excess Fuel

Excess fuel (that generated in excess of the oxidation capability of the available air) is tracked as a potential energy source (rather than mass). Where the room is closed, the excess is collected in the room and the total amount reported in the output. Where there is an open door, the excess is considered to flow out the door and is added to the energy in the special fire data file. This fire data file is then available for use in estimating the impact of the fire on an adjacent room or space or for estimating the extent of flame out of a door or window.

#### h. Response of Heat Detector (or Sprinklers)

The only consideration of sprinklers in FIRE SIMULATOR is as a heat detector. Since FIRE SIMULATOR has no means of determining the impact of activation of a heat detector, the program continues to operate after the activation of the device. This, because the program does not know whether the device is a sprinkler head or heat detector. The response of a heat detector or sprinkler is based on the transfer of heat from the fire produced jet of hot gas flowing across the ceiling to the heat sensitive element. The approach used for these calculations is that developed by Alpert [15]. In this approach, response time index (RTI) characterizes the thermal lag of the sensing element involved. The only heat transfer considered in these calculations is convective heat transfer.

FIRE SIMULATOR calculations also consider the effect of the hot gas layer on the temperature of the ceiling jet. In the approach proposed by Evans [16], an equivalent virtual source is developed. This virtual source calculation relates to the development of the ceiling jet and is not the same as that previously discussed in estimating flame height. This use of a virtual source calculation, however, allows the use of the Alpert correlations to produce a ceiling jet having temperature and velocity that recognizes the impact of the hot gases entrained into the jet as it passes through the hot smoke layer.

An optional adjustment is provided to reduce the ceiling jet velocity in the area of sidewall sprinkler heads. The default value, changeable by the user, is 50%.

#### i. Smoke Detector Activation

Smoke detector activation is identical to that for a heat detector except that the correlation proposed by Heskestad [29] relating the response of smoke detectors to a modest rise in the ceiling jet temperature has been used. The default value for the temperature rise is that recommended by Heskestad for most fuels. This value is 23°F (13°C) rise (i.e., 93°F (34°C) activation temperature if the room temperature is 70°F (21°C)). The value is adjustable by the user if desired.

#### j. Prediction of Flashover

Flashover is considered to be the point which all available fuel surfaces become ignited. In FIRE SIMULATOR, the temperature of the smoke layer is used as the indicator of when this occurs. The temperature can be set by the user. FIRE SIMULATOR includes a default value of 1112°F (600°C).

#### k. Carbon Monoxide and Carbon Dioxide Concentrations.

The concentrations of carbon monoxide and carbon dioxide in the smoke are derived from the assumption that the dominant products of combustion are carbon monoxide, carbon dioxide, and water. It is also assumed that ap-

proximately half of the product produced as the result of combustion of the available air with available fuel is water and the residual is divided between carbon monoxide and carbon dioxide. The ratio of carbon monoxide to carbon dioxide (CO/CO<sub>2</sub> ratio) is estimated as being approximately 0.005 when there is an excess of oxygen (fuel control burning) and 0.5 when there is an excess of fuel (ventilation controlled burning). These values are derived from an analysis made by Mulholland and can be changed by the user. A copy of his memorandum report is included as Appendix C of this document. These values, of course, are a gross approximation. The technology in this area is still being developed. As better algorithms are developed, this estimation can be improved.

It has been observed that the total amount of oxygen atoms can exceed the portion of oxygen atoms in air when an oxygen bearing fuel is burned. Typically, this occurs with wood, paper or other cellulose materials. Conversely the total oxygen atoms are limited to that available from air when non-oxygen bearing hydrocarbons (e.g., petroleum based materials) are burned. For the purpose of FIRE SIMULATOR it is assumed that all materials having heats of combustion close to that for common cellulosic materials contain about the same amount of oxygen atoms and those having higher heats of combustion have proportionally less oxygen atoms. In FIRE SIMULATOR, it is assumed that the fuel is totally composed of cellulosic materials if the heat of combustion is 7000 BTU/pound (about 17 kJ/g) or less and totally composed of non oxygen bearing materials if the heat of combustion is 14000 BTU/pound (about 34 kJ/g). A proportional estimate is made for heats of combustion between these limits.

FIRE SIMULATOR assumes that the maximum increase in oxygen availability is 60% over that depleted by the combustion process and the excess is present in the relative proportions indicated as oxygen bearing materials by the heat of combustion.

Based on the above FIRE SIMULATOR tracks the carbon dioxide, and carbon monoxide concentrations in the smoke layer, the CO/CO<sub>2</sub> ratio produced by the fuel burned, and any excess air entrained in the rising plume. FIRE SIMULATOR then uses a dilution calculation to determine the estimated concentration of carbon monoxide and carbon dioxide in the smoke.

### 1. Vision Distance

Vision distance, visibility through the smoke, is an approximation of the distance at which the smoke blocks 95% of the light from a well lit source. This is developed using a procedure described by Mulholland [30]. The use of this procedure requires a "specific extinction coefficient." A number of such coefficients are reported by Quintiere [31]. The default value used for specific extinction coefficient is 0.1 m<sup>2</sup>/g. This is changeable by the user. The mass concentration used to calculate vision distance is based on rate of mass produced by the burning fuel. This approach simulates the manner in which specific extinction coefficient is derived on the basis of the mass burned in rate of heat release tests. Presently FIRE SIMULATOR uses a single value for specific extinction coefficient through the course of the simulation run. It is known, however, that many materials produce different specific

extinction coefficients as they burn depending on the environment involved. The data, however, is sparse and no algorithm was found for varying the value during a run. The user should expect that the results for vision distance may be reasonable only in that portion of the run where the conditions estimated by the model are similar to those in the test procedure used to develop the specific extinction coefficient used.

#### m. Post Flashover Burning Rates

Once flashover is indicated, FIRE SIMULATOR assumes that all exposed surfaces have become ignited and previous rates of burning are no longer valid. The determination of burning rate is based on incident energy, exposed surface area, and heat of gasification. FIRE SIMULATOR makes a number of assumptions, which are adjustable by the user. The key assumptions in post flashover are the following.

(1) Total flux from the smoke layer to combustible portions of the ceiling walls, floor, or other fuel is 80 kW per square meter.

(2) The average heat of gasification is between 2 kJ/g and 4 kJ/g. With 2 kJ/g used for non-charring materials (assumed to be those represented by high heats of combustion) and 4 kJ/g for charring materials (assumed to be those represented by low heats of combustion.) The effective heat of gasification used is based on the heat of combustion entered by the user. The higher the heat of combustion the lower the heat of gasification within the above range of heats of gasification. The corresponding range of heats of combustion are set to prescribe 4 kJ/g for heats of combustion of 8000 BTU/lb (18.5 kJ/g) or less and 2 kJ/g for heats of combustion of 16,000 BTU/lb. (37 kJ/g) or more. The heat of gasification is linearly proportioned between 2 kJ/g and 4 kJ/g between these heat of combustion limits.

(3) If the burning rate drops below that necessary to maintain ventilation limited burning (drops below that of the calculated ventilation limit), the prime energy feed to the burning material is the flame and the incident flux drops to 60 kW per square meter.

The burning rate is then calculated based on inputs by the user. The user has two options. The user may use a single input assuming that all materials have the same thickness and FIRE SIMULATOR will calculate burning duration.

Alternatively, the user may divide the fuel into three levels of thickness. Default thicknesses in this case are materials less than 1/4" thick, materials greater than 1/4" thick, and materials greater than 1" thick. In such case, FIRE SIMULATOR again determines the time to burnout of each thickness and develops a burning rate based on the surface area available.

FIRE SIMULATOR assumes that the material that is 1/4 inch or thinner will burn out in 300 seconds. That which is greater than 1/4 inch thick and not over 1 inch thick will burn out in 1200 seconds, and that over 1-inch thick will continue to burn until the fuel is exhausted. These values are judgement estimates based on traditional values for wood finishes. In future versions the user will be allowed to change these inputs. In the present version, any

user desiring a different burning duration can approximate such only by adjusting the portions in each of the three preset thickness categories.

In each case, for each thickness, the user inputs the surface area as a horizontal projection of combustible surfaces in terms of percent of the total floor area and a vertical projection of combustible surfaces as a percent of the wall area.

The user also inputs a total fuel load which is used in determining duration.

Using the above data FIRE SIMULATOR calculates the rate of mass loss at each stage by dividing the total incident flux by the heat of gasification and multiplying the result by the heat of combustion. The result is the potential fuel energy available. This is compared to the limits on combustion in the room imposed by the size of the openings and air entrained into the fire plume. The least of these is considered as the rate of energy input in the room. If this is less than the rate of potential fuel production, the excess is considered to be unburned fuel contained in the effluent smoke streams leaving room openings.

### 3. EQUATIONS USED IN FIREFORM

#### 3.1 THE ASETB MODEL

The following description of the mathematics involved in the ASETB model has been abstracted from Walton's original document describing ASETB [11]. Some notes have been added by the author. The notations used by Walton are those common to BASIC computer programming. Walton's notational approach is continued in the discussion of ASETB.

"The mathematical model which is the basis for ASET and thus ASETB has been presented in detail by Cooper [24], and will be only summarized here. It is based on a single room or enclosure with all doors, windows or vents closed except for a small leak at floor level. This leak prevents the pressure from increasing in the room. A fire starts at some point below the ceiling and releases energy and products of combustion. The rate at which energy and products of combustion are released may change with time. The hot products of combustion form a plume, which due to buoyancy, rises towards the ceiling. As the plume rises, it draws in cool air from the room which decreases the plume's temperature and increases its volume flow rate. When the plume reaches the ceiling it spreads out and forms a hot gas layer, which descends with time as the plume's gases continue to flow into it. There is a relatively sharp interface between the hot upper layer and the air in the lower part of room, which in this model is considered to be at ambient temperature. The only interchange between the air in the lower part of the room and the hot upper layer is through the plume. ASET could therefore be described as a two layer or zone model. The basic fire phenomena are shown schematically in figure 1.

"The two unknowns in ASETB are the height of the hot layer interface above the fire,  $Z$ , and the average temperature of the upper layer,  $P$ . The unknowns,  $Z$  and  $P$ , are often referred to as the (dimensionless) height and temperature of the smoke layer since, consistent with the model formulation, smoke can only be found in the plume and the hot upper layer. The known quantities are the area and height of the room,  $A$  and  $H$ , the height of the base of the fire above the floor,  $F$ , and the acceleration due to gravity,  $G$ . In addition, the ambient temperature,  $P_A$ , density,  $D_A$ , and specific heat,  $C_P$ , of air must be known. The final known quantities are the rate at which heat is released by the fire as a function of time,  $Q_T$ , the fraction of the total heat release which is given off as radiation,  $LR$ , and the fraction of total heat release rate which is lost to the contents and surrounding surfaces of the room,  $LC$ .

"The unknown height and temperature are determined by using conservation of mass and energy in conjunction with equations describing the plume. Since the height and temperature of the smoke layer will vary with time,  $T$ , their solutions are obtained by solving two differential equations. In developing the original equations for ASET [20], two dimensionless groups of problem parameters,  $C_1$  and  $C_2$ , were introduced. Also introduced were dimensionless forms of the variables time, height and temperature of the smoke layer, initial height of the smoke layer, height of the base of the fire and the rate of heat release. These variables are made dimensionless by dividing them by a characteristic quantity with the same dimensions or units.



"Thus the dimensionless temperature, P, is the actual temperature of the smoke layer, PF (converted to R), divided by the ambient temperature, PA (R). Similarly, the dimensionless rate of heat release, QT, is the actual rate of heat release, QA (kW), divided by the initial rate of heat release, Q0 (kW). Finally, the dimensionless variables, height of the smoke layer, Z, initial height of the smoke layer, Z0, and height of the base of the fire, F, are the dimensional values for these variables in feet divided by a characteristic length CL which is also in feet. Here as in the ASET program, CL is simply taken as one foot. Thus the dimensionless lengths Z, Z0 and F are the same as their physical lengths in feet. The dimensionless time, T, is the actual time divided by a characteristic time, CT, of one second. The dimensionless time, T, is therefore numerically equal to the actual time in seconds. Since engineering units are used in ASET, this convention has been continued here for consistency.

NOTE: In FIRE SIMULATOR as in ASETB the value of Q0 is a constant set at 0.1 BTU/sec. (0.095 kW).

"The differential equations for the dimensionless height of the layer above the fire, Z, and average temperature of the layer, P, are given below.

NOTE: The following equations are presented in the same format used by Walton [11]. Some of the conventions used are abstracted from the rules for programing in BASIC. In the presentations below the symbol ^ is the indication of an exponent. For example in the expression in equation 5 reading  $QT^{(1/3)}$  is read the variable QT raised to the 1/3 power.

#### a. Height of layer.

"Three different equations are used depending on the position of the smoke level relative to the level of the fire (i.e. normally top of the fuel package that is burning.)

$$\begin{aligned} \frac{dZ}{dT} &= \frac{(-C1*QT) - [C2*QT^{(1/3)}*Z^{(5/3)}]}{0} && \text{when } 0 < Z \leq Z0 \text{ (Layer above fire)} && (1) \\ & && -F < Z \leq 0 \text{ (Layer below fire)} && (2) \\ & && Z = -F \text{ (Layer at floor)} && (3) \end{aligned}$$

#### b. Temperature Change in Smoke Layer.

"Two equations are used depending on the position of the smoke layer relative to the level of the fire.

$$\begin{aligned} \frac{dP}{dT} &= \frac{P*[C1*QT - (P-1)*C2*QT^{(1/3)}*Z^{(5/3)}]}{P*C1*QT/(Z0-Z)} && \text{when } 0 < Z < Z0 && (4) \\ & && -F \leq Z \leq 0 && (5) \end{aligned}$$

### c. Dimensionless groups.

"The equations for the dimensionless groups C1 and C2 are given below.

NOTE: In the traditional application of ASETB all of the variables in both C1 and C2 are constant through the course of any numerical solution to the above equations. In the ASETB form C1 and C2 are calculated at the start of the computations and used as a constant from that point on. In the adaptation used in FIRE SIMULATOR, the heat transfer factor LC is internally calculated and adjusted each second of fire simulation. In FIRE SIMULATOR the value of C2 is constant for the application but the value of C1 is recalculated each time step of calculation.

$$C1 = (1 - LC) * Q0 * CT / (DA * CP * PA * A * CL) \quad (6)$$

$$C2 = (0.21 * CT / A) [ (1 - LR) * Q0 * G * CL^2 / (DA * CP * PA) ]^{(1/3)} \quad (7)$$

"In order to solve the equations for Z and P the initial conditions must be known. One set of initial conditions which were derived in [19], and will be used here, assume that the fire starts with a small heat release rate, Q0, at time T=0. Under such conditions the initial conditions are.

$$Z = Z0 \quad (8)$$

$$P = 1 + Z0^{(-5/3)} * C1 / C2 \quad (9)$$

"Although dP/dT is indeterminate in the above equation at T=0 its actual value has been found in [20] to be.

$$dP/dT = (C1/C2) [ 2 * DQ0 + 5 * (C1 + C2 * Z0^{(5/3)}) ] / (6 * Z0^{(8/3)}) \quad (10)$$

Where  $DQ0 = dQT/dT$  at time T=0. "

### 2. ATRIUM SMOKE TEMPERATURE.

The equation used in ATRIUM SMOKE TEMPERATURE, developed by Cooper [4], is

$$T_{uF} = 400 / \{ 1 + [ 5.3 / (q^{2/3}) z^{5/3} ] \} \quad (11)$$

where  $T_{uF}$  = Temperature rise (°F).  
q = Rate of Heat Release (BTU/sec).  
z = Clear height (from base of fire to smoke layer in ft.)

Cooper [4] advises that the equation is inappropriate in any case where the level of energy exceeds that prescribed by the following relationship.

$$q(\text{limit}) = [(z/.39)^{5/2}]/.65 \quad (12)$$

where  $q(\text{limit})$  = The maximum rate of heat release permitted for the clear space indicated.

### 3.3 BUOYANT GAS HEAD.

The equation used in BUOYANT GAS HEAD is

$$\Delta P = 7.64(1/T_o - 1/T_f)h_i \quad (13)$$

where  $\Delta P$  = Pressure Difference (inches of water)  
 $T_o$  = Absolute value of room temperature (Set at 530°R)  
 $T_f$  = Absolute temperature of the hot gas column (°R)  
 $h_i$  = The height of interest of the hot gas column (ft)

### 3.4 CEILING JET TEMPERATURE.

The equation used in CEILING PLUME JET TEMPERATURE is

$$T_{JF} = T_{oF} + [92(Kz_c/r_i)^{2/3}/z_c] \quad (14)$$

where  $T_{JF}$  = Plume gas temperature (°F)  
 $T_{oF}$  = Room temperature (°F)  
 $K = 1$  when the fire is away from any walls  
 $2$  when the fire is near a wall  
 $4$  when the fire is in a corner  
 $z_c$  = Vertical distance from fire to ceiling (ft)  
 $r_i$  = Lateral distance across ceiling from a point directly over the fire to the point of interest (ft)

### 3.5 CEILING PLUME TEMPERATURE.

The equation used in CEILING PLUME TEMPERATURE is

$$T_{pF} = T_{oF} + [300(Kz_i^{2/3})/(z_i^{5/3})] \quad (15)$$

where  $T_{pF}$  = Plume gas temperature (°F)  
 $T_{oF}$  = Room temperature (°F)  
 $K = 1$  when the fire is away from any walls  
 $2$  when the fire is near a wall  
 $4$  when the fire is in a corner  
 $z_i$  = Distance above base of fire (ft)

### 3.6 EGRESS TIME.

The equations used in EGRESS TIME are

$$Z = X/100 \quad (16)$$

where  $Z$  = Adjustment factor for considering mobile but slow moving persons (Ratio of speed of slow moving individual to that of an able person.)  
 $X$  = Speed of slowest evacuees as % of that of an able person.

$$t_e = P/(60E) \quad (17)$$

where  $t_e$  = Time to clear population through exit doors (min)  
 $P$  = Exiting population (persons)  
 $E$  = Number of exit door leaves available to evacuees

$$t_h = L_1/v_1 \quad (18)$$

where  $t_h$  = Time required for a fully able person to travel the total length of all portions of the exit route that are level (min)  
 $L_1$  = Total length of all portions of exit route that are level (ft)  
 $v_1$  = Unimpaired egress speed on level passages (ft/min)

$$t_{st} = L_v/V_v((1.57h_r/w_t)^{1/2}) \quad (19)$$

where  $t_{st}$  = Time required for a fully able person to travel the total length of all portions of the exit route that are over stairs (min)  
 $L_v$  = Portion of exit travel over stairs (vertical distance in feet)  
 $V_v$  = Unimpaired egress speed on stairs (vertical ft/min)  
 $h_r$  = Stair riser (inches)  
 $w_t$  = Stair tread (inches)

$$t_{dis} = (t_h + t_{st})Z \quad (20)$$

where  $t_{dis}$  = Time required for most distant person to reach an exit without any delay due to bottlenecks at doors (min)

$$K_e = P/J/Be \quad (21)$$

where  $K_e$  = Time constraint caused by stair width (min)  
 $J$  = Total effective width of all stairs involved (ft) (actual width less 1-ft per stair)  
 $Be$  = Flow rate (persons per min per foot effective width)

## 7. FIRE/WIND/STACK FORCES ON A DOOR.

The equations used in FIRE/WIND/STACK FORCES ON A DOOR are

### a. Fire Forces:

$$F_f = 39.7 z_m (1/T_o - 1/T_s) \quad (22)$$

where  $F_f$  = Average fire induced pressure (lbs/ft<sup>2</sup>)  
 $z_m$  = Mid-height of portion of door covered by hot fire gases (ft)  
 $T_o$  = Absolute value of room temperature (Set at 530°R)  
 $T_s$  = The average absolute temperature of the hot gas layer (°R)

$$E_f = R/2 \quad (23)$$

where  $E_f$  = Fire produced force on the latch edge of the door (lbs)

$$R = 2 z_m w_d F_f \quad (24)$$

where  $w_d$  = Width of door (ft)

### b. Wind Forces:

$$F_w = 0.0015 V_w^2 \quad (25)$$

where  $F_w$  = Wind force on door (lbs/ft<sup>2</sup>)  
 $V_w$  = Wind speed (miles per hour)

$$E_w = A_d F_w / 2 \quad (26)$$

where  $E_w$  = Wind produced force on the latch edge of the door (lbs)  
 $A_d$  = Area of door (ft<sup>2</sup>)

### c. Stack Effect Forces:

This equation assumes a neutral plane 3/4 of the building height above grade.

$$F_s = 19.7 h_b (1/T_e - 1/T_o) \quad (27)$$

where  $F_s$  = Average force of stack effect induced pressure (lbs/ft<sup>2</sup>)  
 $h_b$  = Height of building (ft)  
 $T_e$  = Exterior temperature (°R)

$$E_s = A_d F_s / 2 \quad (28)$$

where  $E_s$  = Stack effect produced force on the latch edge of the door (lbs)

### 8. MASS FLOW THROUGH A VENT.

Iteration of the following set of equations is used in MASS FLOW THROUGH A VENT

$$y_2 = 1 / \{ (1 + [T_u / T_{out}]^{1/3}) (1 + m_f / m_i)^{2/3} \} \quad (29)$$

where  $y_2$  = The position of the neutral plane in the opening measured as the ratio of the distance from the base of the opening to the height of that opening.  
 $T_u$  = Upper layer (smoke) temperature (K)  
 $T_{out}$  = Temperature of incoming air (K)  
 $m_f$  = Mass burning rate (g/s)  
 $m_i$  = Mass inflow of air (g/s)

$$m_o = 2/3 M_o C \rho_a (2g)^{1/2} w_o h_o^{3/2} \quad (30)$$

where  $C$  = Opening flow coefficient (0.7)  
 $\rho_a$  = Density of outside air (g/m<sup>3</sup>)  
 $g$  = Acceleration of gravity (9.8 m/s)  
 $w_o$  = Width of opening (m)  
 $h_o$  = Height of opening (m)

$$M_o = [((T_u - T_{out}) / T_{out})^{1/2} / (1 + ((T_u - T_{out}) / T_{out}))] (1 + y_2)^{3/2} \quad (31)$$

$$m_i = m_o - m_f \quad (32)$$

### 9. LATERAL FLAME SPREAD.

The equation used in LATERAL FLAME SPREAD is

$$V_{f1} = (\phi / (k\rho c) / (T_i - T_{su})^2) \quad (33)$$

where  $V_{f1}$  = Lateral flame spread (m/sec)  
 $\phi$  = Ignition factor from flame spread test data (kW<sup>2</sup>/m<sup>3</sup>)  
 $k\rho c$  = Thermal inertia (the product of thermal conductivity, density, and specific heat). The effective thermal inertia is measured as a single value by the test procedure in reference [14]. (kW<sup>2</sup>-s/m<sup>4</sup>-K<sup>2</sup>)  
 $T_i$  = Ignition temperature (°C)  
 $T_{su}$  = Surface temperature (°C)

#### 10. LAW'S SEVERITY CORRELATION.

The equation used to express LAW'S SEVERITY CORRELATION is

$$t_m = 4.9F_1 / ((A_v A_I)^{1/2}) \quad (34)$$

where  $t_m$  = Fire Severity (min)  
 $A_v$  = Area of Ventilation Opening [window or door] (ft<sup>2</sup>)  
 $A_I$  = Interior surfaces to which heat is lost [walls + ceiling] (ft<sup>2</sup>)

NOTE: Heat loss to the floor is assumed to be negligible.

$F_1$  = Total fire load in equivalent pounds of wood

#### 11. PLUME FILLING RATE.

The equation in PLUME FILLING RATE is

$$Q = 5.8(1 - \chi_r)q + 18((1 - \chi_t)q)^{1/3}(z_i)^{5/3} \quad (35)$$

where  $Q$  = Volume flow rate (cfm at height  $z_i$  above fire source)  
 $q$  = Rate of heat release (BTU/sec)  
 $\chi_r$  = Radiant fraction (portion of energy radiated from the flame)  
 $\chi_t$  = Total heat loss fraction (radiant fraction + other losses)  
 $z_i$  = Height of interest (in fire plume) above fire source

#### 12. RADIANT IGNITION OF A NEAR FUEL.

The equations used in RADIANT IGNITION OF A NEAR FUEL are

For easily ignited materials (ignition assumed if incident radiation reaches 10 kW/m<sup>2</sup>):

$$q_{ig} = 30(\text{antilog}_{10}((d_s + .08038)/.88557)) \quad (36)$$

where  $q_{ig}$  = Energy level of source fire at time of ignition of exposed item at distance  $d_s$  (kW)  
 $d_s$  = Separation between the item on fire and the exposed item (m)

For normally ignitable materials (ignition assumed if incident radiation reaches 20 kW/sq m"

$$q_{ig} = 30((d_s + .05041)/.01878) \quad (37)$$

For hard to ignite materials (ignition assumed if incident radiation reaches 40 kW/sq m"

$$q_{ig} = 30((d_s + .02167)/.00918) \quad (38)$$

### 3.13 SMOKE FLOW THROUGH AN OPENING.

The equation used in SMOKE FLOW THROUGH AN OPENING is

$$Q = 7214 A_o ((1/T_o - 1/T_s)^{1/2}) (h_s^{1/2}) ((T_s/T_o)^{1/2}) \quad (39)$$

where

Q = Volume flow rate (cfm)

A<sub>o</sub> = Area of that portion of the opening flowing smoke (sq ft)

T<sub>o</sub> = Absolute value of room temperature (Set at 530°R)

T<sub>s</sub> = The average absolute temperature of the hot gas layer (°R)

h<sub>s</sub> = The vertical distance from the base of the hot layer to the center of the opening (ft)

The equation has been derived from those presented by Klote and Fothergill [8] in their manual Design of Smoke Control Systems for Buildings. Equations 2.5a, 2.2, and 2.5 from that manual were used to derive the equation for this procedure as follows.

$$Q = 2610 A_o ((\Delta P)^{1/2}) \quad (40)$$

$$\Delta P = 7.64 (1/T_o - 1/T_s) h_s \quad (41)$$

$$Q = A_o ((2(\Delta P)/\rho)^{1/2}) \quad (42)$$

where

ΔP = pressure difference across the flow path (in inches of water)

ρ = density of air entering the flow path (lb/ft<sup>3</sup>)

### 3.14 SPRINKLER/DETECTOR RESPONSE.

The equations used in SPRINKLER/DETECTOR RESPONSE are

$$R_h = r/h \quad (43)$$

where

R<sub>h</sub> = Ratio of radial distance from center line of fire plume to position of heat actuated device

r = radial distance from center line of plume to device

h = distance from the burning material the ceiling

$$\text{If } R_h < 0.18$$

$$D_T = 6.18 \quad (44)$$



If  $R_h \geq 0.18$

$$D_T = 1.97R_h^{-2/3} \quad (45)$$

where  $D_T$  = A derived relationship used in subsequent calculations. The values shown are for distances in m and temperatures in K.

$$T_j = D_T / \{ [c_0^2 P_0^2 g h^5 / (T_s q_2^2)]^{1/3} + T_s \} \quad (46)$$

where  $T_j$  = Temperature of ceiling jet at position of heat actuated device

If  $R_h < 0.15$

$$D_U = 3.16 \quad (47)$$

If  $R_h \geq 0.15$

$$D_U = 0.65R_h^{-5/6} \quad (48)$$

where  $D_U$  = A derived relationship used in subsequent calculations. The values shown are for distances in m and temperatures in K.

$$U_M = D_U / [c_0 T_s P_0 h_2 / (g q_2)]^{1/3} \quad (49)$$

where  $U_M$  = Velocity of ceiling jet at position of heat actuated device (m/s).

$$T = R_{ti} / U_M^{1/2} \quad (50)$$

where  $T$  = Heat transfer time constant.  
 $R_{ti}$  = Response time index of heat actuated device.

$$T_L = \{ (T_{jy} - T_{Ly}) (e^{1/T}) + (T_j - T_{jy})^T [e^{-1/T} + (1/T) - 1] \} + T_{Ly} \quad (51)$$

where  $T_L$  = Temperature of heat actuated element ( $^{\circ}\text{C}$ ).  
 $T_{Ly}$  = Temperature of heat actuated element at previous time increment in calculation ( $^{\circ}\text{C}$ ).  
 $T_{jy}$  = Temperature of ceiling jet at previous time increment in calculation ( $^{\circ}\text{C}$ ).  
 $e$  = Natural log base.

When  $T_L$  equals the temperature rating of the heat actuated device, the device is considered to be actuated.

### 3.15 THOMAS' FLASHOVER CORRELATION.

The equation used to express THOMAS' FLASHOVER CORRELATION is

$$Q_{fo} = 20A_v(h_v^{1/2}) + 0.75A_s \quad (52)$$

where  $Q_{fo}$  = Flashover Energy (BTU/sec)  
 $A_v$  = Area of Ventilation Opening [window or door] (ft<sup>2</sup>)  
 $h_v$  = Height of Ventilation Opening (ft)  
 $A_s$  = Interior Surface of Room [walls + ceiling + floor] (ft<sup>2</sup>)

### 3.16 UPPER LEVEL TEMPERATURE.

The equation used in UPPER LEVEL TEMPERATURE is

$$T_u = T_o + \{6.85(q^2/[A_v h_v^{1/2} h_k A_s])^{1/3}\} \quad (53)$$

where  $T_u$  = Upper layer temperature (°C)  
 $T_o$  = Room temperature (°C)  
 $q$  = Rate of heat release (kW)  
 $A_v$  = Area of Ventilation Opening [window or door] (m<sup>2</sup>)  
 $h_v$  = Height of Ventilation Opening (m)  
 $A_s$  = Interior Surface of Room (m<sup>2</sup>)  
 $h_k$  = Effective enclosure conductance

The calculation of effective enclosure conductance is a function of the thermal properties of the room linings, the thickness of these linings, and the duration of fire exposure. A two step process is provided in this program using the following.

Step 1. Thermal penetration time. As used in this procedure the time for a thermal pulse to penetrate a lining material is given by

$$t_p = (\rho c/k)((d/2)^2) \quad (54)$$

where  $t_p$  = Thermal penetration time (sec)  
 $\rho$  = Density (kg/m<sup>3</sup>)  
 $c$  = Specific heat (kJ/kg·K)  
 $k$  = Thermal conductivity (kW/m·K)  
 $d$  = Thickness (m)

Step 2.

a. If  $t_p$  is less than the fire duration time then

$$h_k = ((k\rho c/t)^{1/2}) \quad (55)$$

where  $h_k$  = Effective enclosure conductance  
 $t$  = fire duration time (sec)

b. If  $t_p$  is equal to or greater than the fire duration time then

$$h_k = k/d \quad (56)$$

#### 17. VENTILATION LIMIT.

The equation used in VENTILATION LIMIT is

$$q_L = k_a e_a w_o h_o^{3/2} \quad (57)$$

where

- $q_L$  = Rate of energy release supportable by air from opening
- $k_a$  = A derived constant
- $e_a$  = Efficiency of use of available air
- $w_o$  = Width of opening
- $h_o$  = Height of opening

When opening dimensions are in m the value of k is approximately 1500 and  $q_L$  is in kW.

### Chapter 4. Equations Used in MAKEFIRE

#### 1. General.

Two of the fire routines in MAKEFIRE use equations. These two are FREEBURN and FORMULA. FREEBURN includes an ignition calculation and FORMULA includes two optional fire growth equations.

#### 2. DESCRIPTION OF IGNITION CALCULATIONS INVOLVED IN FREEBURN.

In order to estimate the moment of ignition of an exposed fuel package FREEBURN:

- (1) Estimates the radiant emission from each burning fuel package.
- (2) Calculates the approximate radiant impact on each unignited fuel package.
- (3) Assumes ignition of a previously unignited fuel package when (at the direction of the user):
  - (a) A prescribed period of exposure is reached.
  - (b) A prescribed level of incident radiant energy is reached.
  - (c) A prescribed surface temperature is reached.

#### a. Radiant Emission from Ignited Fuel Package.

To operate FREEBURN requires the input of fire descriptions as a series of pairs of times and the rate of heat release at those times. The only form of this input accepted by FREEBURN is as a fire data file such as developed by other routines in the MAKEFIRE collection.

FREEBURN estimates the radiant fraction for each fuel. The default value is .35 (35%). This establishes the radiant emission from each ignited fuel package as a fraction of the rate of heat release at any time. FREEBURN assumes that the emissivity of the initial small flame is low and that the full expected radiant fraction is not achieved until a significant rate of heat release is present. The default value used is 994 BTU/sec (1MW). FREEBURN makes a linear adjustment in the emitted radiation for any rate of heat release less than this level. The adjusted value is proportional to the actual rate of heat release divided by the rate of heat release specified as a significant fire.

#### b. Radiant Impact on Target Fuel Package.

FREEBURN calculates the approximate radiant impact on an exposed fuel package based on the relationships proposed by Modak [21] for pool fires. The prime equation is

$$q_i = Q_o / 4\pi r_c^2 \quad (58)$$

where

- $Q_o$  = Total radiant flux from the exposing fuel package
- $q_i$  = Incident flux per unit area on unignited fuel package
- $r_c$  = Distance between the effective center of the fire and the surface of the target fuel package

FREEBURN estimates the effective center of a burning fuel package using the default assumption of a burning rate of 100 BTU/ft<sup>2</sup> (1079.3 kW/m<sup>2</sup>) of involved area. The fire is assumed to be circular with the edge of the circle closest to the exposed fuel package at the point that the user enters as the distance from the exposed package. Value of  $r$  is then equal to the prescribed distance plus the radius of the calculated circular fire. A maximum of 1.64 ft. (1/2 m) is the default setting for the maximum assumed radius. This maximum reflects the assumption that larger diameter fires will be optically thick and there will be no increase in the distance to the effective center of the fire.

Equation (58) is more accurate as the distance from the effective center of the fire to the target fuel package increases. Where the relative ratio of the effective fire radius to the distance  $r$  is small, an error exists. Modak [21] provides measurements that allows estimates of the error. Figure 2 is a curve from his paper showing measurements he made. The average of the two curves shown has been converted into a table. In FIRE SIMULATOR this table is used to adjust the incident radiation where the ratio of the radius of the fire to the distance  $r$  is 10 or less.

### c. Ignition of Exposed Fuel Package.

The user may specify different modes of ignition criteria for different fuel packages but only one mode for any single fuel package. If the user prescribes either a period of time or an incident radiant energy there are no calculations performed by FREEBURN. If, however, the user specifies ignition based on a prescribed surface temperature FREEBURN executes the following integration.

$$(T_{ig} - T_{su}) = \int_0^t \frac{q_e(t') dt'}{[\pi(t-t')(k\rho c)]^{1/2}} \quad (59)$$

where

$T_{ig}$	=	Prescribed ignition temperature
$T_{su}$	=	Surface temperature of exposed fuel package
$q_e$	=	Radiant flux striking target fuel at time $t$
$t$	=	Duration of exposure
$t'$	=	Increment of integration (the program uses 1 second)
$k\rho c$	=	Thermal inertial of exposed surface of unignited fuel package

The value of  $t$  increases with each time cycle (second) of the computation. This requires a total repeat of the integration each iteration of the program. When  $(T_{ig} - T_{su}) = 0$ , ignition is presumed.

### 4.3 Fire growth equations used in FORMULA

FORMULA creates fire data files based on the use of power law or exponential growth equations as selected by the user.

The power growth equation is

$$q = at^n \quad (60)$$

where

$q$	=	Rate of heat release (Kw or BTU/sec at user's choice)
$a$	=	A constant (suggested values are included in the routine)
$t$	=	Time since initiation (s)
$n$	=	An exponent (usually 2 in which case the fire is referred to as a $t^2$ fire)

The exponential equation is

$$q = Be^{bt} \quad (61)$$

where

$q$	=	Rate of heat release (kW or BTU/sec at user's choice)
$B$	=	Constant (In FORMULA $B$ is set at 1kW if metric dimensions are specified and 1 BTU/s if English dimensions are specified)
$e$	=	$e$ (the base of natural logarithms)

b = A constant (the suggested values included in the routine)  
t = Time since initiation (s)

## 5. EQUATIONS USED IN FIRE SIMULATOR

### 5.1 DESCRIPTION OF THE ASETB MODEL

FIRE SIMULATOR is based on the room fire model ASETB. The equations used are described in paragraph 1 of chapter 3.

### 5.2 ADJUSTMENTS FOR DOORS OR OTHER OPENINGS AND FOR HVAC

#### a. Ventilation Limit.

FIRE SIMULATOR uses the concept of ventilation limit in several routines. Ventilation limit marks the demarcation between free burning conditions and ventilation limited conditions. The ventilation limit is defined as the maximum amount of energy that can be supported by the air drawn into the space through openings or provided by mechanical systems. FIRE SIMULATOR provides for a maximum of two openings and one HVAC value. Each of these are calculated individually. Each opening therefore develops a ventilation limit for that opening and the HVAC system has another ventilation limit. The ventilation limit for the space is the sum of each of these. The equations are detailed in paragraph 2.c, below.

#### b. Impact of Residual Air on Ventilation Limit

When ventilation limit occurs in the opening, the fire will be restricted to a burning rate not exceeding that supportable by the air supply unless there is a quantity of residual air in the space. This can be a factor in large rooms. Once the ventilation limit conditions have been reached, FIRE SIMULATOR checks the amount of residual air available for combustion with each cycle and prohibits the ventilation limit from impacting on burning rate so long as that air is available.

#### c. Volume flow.

Once the smoke level descends below the soffit of the highest opening the out-flow of smoke is estimated using an adaptation of the equations for flow through an opening developed in FIREFORM. Since all openings considered in FIRE SIMULATOR are in a vertical plane it is necessary to determine the hydrostatic mid point of the portion of the opening covered by smoke. This has been determined to be a point 4/9 of the distance from the bottom of the smoke layer to the top of the opening. In engineering units as used in FIREFORM the equation is expressed as follows.

$$Q = 7214A_o (1/T_o - 1/T_s)^{1/2} [(4/9)(h_s)]^{1/2} (T_s/T_o)^{1/2} \quad (62)$$

where  $Q$  = Volume flow rate (cfm)

$A_o$  = Area of that portion of opening flowing smoke ( $\text{ft}^2$ )

$T_o$  = Initial room temperature (Assumed to be  $530^\circ\text{R}$  in FIRE SIMULATOR)

$T_s$  = Temperature of smoke ( $^\circ\text{R}$ )

$h_s$  = Height of portion of opening flowing smoke (ft above base of smoke layer)

(If smoke descends below sill of opening then the term  $[(4/9)(h_s)]$  is revised to equal the distance from the base of the smoke layer to the sill plus  $4/9$  the actual height of the opening)

The quantity  $Q$  is deducted from the volume increase in the smoke layer calculated by the ASET core model and the rate of descent of the smoke appropriately retarded.

When ventilation limited conditions exist, the smoke flow through the opening is calculated using the following equation. The value obtained is also considered the maximum flow in both terms of volume and enthalpy through the opening using the following equation.

$$Q = q_L / (\rho_s Hc_{air}) \quad (63)$$

where

$Q$  = Volume flow rate ( $\text{m}^3/\text{s}$ )

$q_L$  = Ventilation limit (kW)

$\rho_s$  = Density of smoke layer ( $\text{g}/\text{m}^3$ )

$Hc_{air}$  = Heat of combustion (oxidation capacity) of air (i.e.  $3\text{kJ}/\text{g}$ )

Functionally for  $Q$  in cfm this becomes  $0.6q_L (T_s/T_o)$  (64)

#### d. Enthalpy losses.

The loss of energy (enthalpy) is calculated using the equation.

$$q_{ent} = m_s C_p (T_s - T_o) \quad (65)$$

where

$q_{ent}$  = Energy (enthalpy) in out-flowing smoke as a rate (kW)

$m_s$  = Mass flow of smoke ( $\text{g}/\text{s}$ )

$C_p$  = Specific heat of smoke (considered same as specific heat of air) ( $\text{kJ}/\text{g-K}$ )

$T_s$  = Temperature of smoke layer (K)

$T_o$  = Temperature of incoming air (assumed by FIRE SIMULATOR to be room temperature) (K)

The enthalpy loss is treated as an additional energy loss. In FIRE SIMULATOR this is accomplished by deducting the energy lost in any second from the energy entering the smoke layer in the following second.

#### e. Impact on the position of smoke layer.

The basic ASET core model in FIRE SIMULATOR accounts for the descent of the smoke layer as an increasing volume of smoke body. FIRE SIMULATOR accepts this and deducts from that volume the amount of smoke calculated as venting through the openings or removed by the hvac system as described above. As the fire varies, the amount of smoke vented may be equal to, greater than, or less than the rate of smoke filling. In view of this, the smoke may descend, rise, or stay at a fixed location.

If, however, the room has an opening, a neutral plane will be established when the mass flow out reaches a point where flow is restricted by the competing mass flow in. The neutral plane establishes itself so that in-flow and out-flow are in mass balance. The position of this neutral plane is primarily a function of the temperature of the out-flowing smoke and the in-flowing air. The equations for calculating this relationship are detailed in the discussion of MASS FLOW THROUGH A VENT in FIREFORM (See Chapter 3.) FIRE SIMULATOR approximates this relationship as a function of smoke temperature. Exercising the mass flow routine for conditions with a wide range of temperatures, opening sizes, and opening height to width ratios resulted in the following relationships used by FIRE SIMULATOR to estimate the position of the neutral plane.

For  $T_s \leq 1000^\circ\text{F}$  ( $538^\circ\text{C}$ )

$$N_a = [(T_s - T_0) * .0000889] + .51 \quad (66)$$

For  $T_s > 1000^\circ\text{F}$  ( $538^\circ\text{C}$ )

$$N_a = [(T_s - 1000) * .00002] + .59 \quad (67)$$

Where  $T_s$  = Smoke temperature (Degrees F)  
 $T_0$  = Room temperature (Assumed by FPETOOL to be 70 F)  
 $N_a$  = Portion of opening above neutral plane

FPETOOL restricts the level of smoke in the opening to the portion of the opening determined by the above equations. The level in the room is, however, allowed to descend below the neutral plane.

### 5.3 CALCULATION OF HEAT LOSS FACTOR

#### a. General.

FIRE SIMULATOR uses the ASETB [11] equations for estimating mass and temperature in the smoke layer. The equations require heat loss within the fire room expressed as a portion of the rate of energy released in the space. FIRE SIMULATOR calculates convective heat transfer from the smoke layer to the wall and ceiling surfaces in contact with the smoke. It also calculates radiant losses from the smoke layer. A user adjustable estimate is made of the radiant loss from the flame. The default value for this estimate is .35 (35%). These losses are summed and divided by the rate of energy input to derive the loss factor required by the ASETB equations.



### b. Bounding Limits.

In addition to the above calculations several limits to the range of the heat loss factor are included in FIRE SIMULATOR as follows.

- (1) A user adjustable maximum heat loss factor is established with a default value of .95. The user however is provided with advice suggesting a lower value for rooms with high aspect ratio of room area to distance from the fire to the ceiling.
- (2) FIRE SIMULATOR also establishes a maximum heat loss factor of 0.8 in any condition where the room temperature exceeds 572°F (300°C).
- (3) In any case, where the rate of energy input decreases during the course of the fire, FIRE SIMULATOR allows the maximum heat loss factor to rise proportionally to the decrease in rate of heat release. This is limited to application during the periods of descending rates of heat release.

### c. Specific Calculations.

The overall equation for heat loss factor is

$$L_c = (q_r + q_c + q_f) / q_p \quad (68)$$

where

- $L_c$  = Heat loss factor
- $q_r$  = Radiation lost from smoke layer
- $q_c$  = Convective losses from smoke layer to walls and ceiling
- $q_f$  = Radiant loss directly from flame (default value = .35)
- $q_p$  = Actual rate of energy release from fire

In equation (67) the value for  $q_f$  is preset at .35 unless adjusted by the user. The value of  $q_p$  is derived from the data entered by the user but may be adjusted elsewhere in FIRE SIMULATOR (See preceding paragraph 2, Adjustments for Doors or Other Openings and for HVAC; and paragraph 4, Calculation of Combustion Limits Due to Limited Oxygen Availability for adjustment made by FIRE SIMULATOR) The values for  $q_r$ , radiation from the smoke layer, and  $q_c$ , convective losses from the smoke layer are derived from the following calculations.

#### (1) Radiation from Smoke Layer.

FIRE SIMULATOR assumes that radiation exchange between the smoke layer and the ceiling and the portion of the walls in contact with the smoke layer is a function of the temperature difference between the smoke layer and those surfaces. In the pre-flashover stage FIRE SIMULATOR assumes that radiation from the lower surface of the smoke layer is to the floor or other surfaces that are at room temperature (70°F, 21°C)

After flashover, FIRE SIMULATOR assumes that there is no heat loss from the hot gas body to any burning surface. The extent of burning surface is based on the user inputs describing the extent of combustible surface. The heat input from the burning surfaces is presumed to be included in the calculations for rate of heat release from those surfaces. Radiation from the smoke layer is considered a minor factor when the smoke layer is cool (i.e. less than 750°F - 400°C). FIRE SIMULATOR assumes an emissivity of 0.1 at temperatures less than that value rising rapidly to 1.0 as the smoke layer temperature rises to 1100°F (600°C). This value is felt appropriate for the hot smokey conditions normally encountered in fully involved accidental fires. The radiation transfer equation used is

$$q_r = \epsilon_g \sigma (T_s^4 - T_w^4) A_w \quad (69)$$

where

- $q_r$  = Radiation loss from smoke (to surface(s)  $A_w$ ).
- $\epsilon_g$  = Emissivity of hot smoke gases (default value is 1.0)
- $\sigma$  = Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2\text{-K}$ )
- $T_s$  = Temperature of smoke layer (K)
- $T_w$  = Temperature of surface receiving radiation (K)
- $A_w$  = Area of surface receiving radiation from smoke layer

## (2) Surface temperatures.

The temperature of involved wall and ceiling surfaces ( $T_w$ ) is derived from the following.

$$(T_w - T_0) = \frac{(h_c + 4\epsilon_g T_g^3 \sigma)(T_g - T_0)}{h_w + h_c + 4\epsilon_g T_g^3 \sigma} \quad (70)$$

where

- In addition to the variable defined for equation (69)
- $T_0$  = Absolute value of ambient temperature (294K in FIRE SIMULATOR)
- $h_c$  = Convective heat coefficient (Assumed as 20 W/m<sup>2</sup>-K in FIRE SIMULATOR)
- $h_w$  = Effective conductive heat loss coefficient (Derived as described below)

## (3) Effective conductive heat loss coefficient.

The value of  $h_w$ , effective conductive heat loss coefficient, varies with both the thermophysical properties of the materials involved and the duration of exposure. The approach is derived from the work of Quintiere [26] and McCaffrey et. al. [25.] Two regimes are involved. The equation used for the initial regime varies with time of exposure and accounts for the ability of the material to absorb and conduct energy. The equation used is

$$h_w = (k\rho c/t)^{1/2} \quad (71)$$

where      k = Thermal conductivity  
              ρ = Density  
              c = Specific heat  
              t = Time of exposure

The second regime starts when the exposed surface has reached a state where most, if not all, of its ability to absorb or internally distribute energy is exhausted. The equation used for this regime is

$$h_w = k/d \quad (72)$$

where      d = Thickness of the material measured from the exposed face

The transfer from the first to the second regime is based on the following equation estimating the time when diffusion and absorption capabilities are no longer a factor. This is approximately equal to the time for a thermal pulse to penetrate to the unexposed side of the surface. The equation used is

$$t_p = (\rho c/k)(d/2)^2 \quad (73)$$

where       $t_p$  = Time of exposure when calculation is transferred from the first to the second regime (sec)

FIRE SIMULATOR accommodates up to 3 ceiling and 3 wall materials. The impact of the different materials with different properties and thickness is handled by separately calculating the individual values of  $h_w$ . This is done at each iteration of FIRE SIMULATOR. A weighted average value based on exposed area of each surface in contact with the smoke layer is used.

#### 5.4 CALCULATION OF COMBUSTION LIMITS DUE TO LIMITED OXYGEN AVAILABILITY

The extent to which the material pyrolyzed can burn within the room of origin, is limited by the availability of air for combustion. Two limiting factors control this availability as follows.

##### a. Limitation due to air supplied from openings and HVAC equipment.

Two equations are involved.

##### (1) Air from openings.

The combustion supportable by air drawn into the room through openings is determined by the following widely accepted relationship for an elevated temperature enclosure fire (originally proposed by Kawagoe [19].)

$$q_L = k_a e_a w_o h_o^{1/2} \quad (74)$$

where  $q_L$  = Rate of energy release supportable by air from opening  
 $k_a$  = A derived constant  
 $e_a$  = Efficiency of use of available air (100% in FIRE SIMULATOR)  
 $w_o$  = Width of opening  
 $h_o$  = Height of opening

If opening dimensions are in m  $k$  is approximately 1500. ( $\text{Kj-m}^{2/5}\text{-s}^{-1}$ )

## (2) Air from mechanical (HVAC) systems.

FIRE SIMULATOR calculates the ability of the air supplied by forced movement (fans, stacks, or other devices) to support combustion by determining the oxidation capability of the mass of that air volume. The oxidation capability of air is based on the value reported by Huggett [27] of 13.1 kJ of energy per gram of oxygen consumed (3kJ of energy per gram of air.) This is determined by the following relationship.

$$q_h = 3000e_a m \quad (75)$$

Where  $q_h$  = Rate of energy release supportable by air supplied by mechanical means, primarily the HVAC system (kW)  
 $e_a$  = Efficiency in the use of this air  
 (FIRE SIMULATOR uses a default value of 1.0 (100%) for  $e_a$ . This assumes that, at the point of ventilation limit, all of the air supplied will be involved in the combustion process. FIRE SIMULATOR permits the user to make a judgement based adjustment to the value of  $e_a$ . Such is important if the arrangement of the supplied air is not conducive to complete mixing with fuel gases and the resulting combustion.)  
 $m$  = Mass rate of air flow in kg/s

In FIRE SIMULATOR the individual values of  $q_L$  from each opening are added to the value of  $q_h$  to derive a maximum combustion capability (referred to as ventilation limit.) If the potential energy available from pyrolysis is greater than the ventilation limit, FIRE SIMULATOR limits the rate of heat release to that determined by the available air. Excess pyrolysis products are considered to be vented in the out flowing fire products. FIRE SIMULATOR tracks those products.

## b. Limitation due to inability to entrain sufficient air in fire plume.

As the fire develops and the smoke layer descends the rising fire plume entrains mass from both above and below the smoke layer. FIRE SIMULATOR assumes that the mass entrained below the smoke layer is clear air (i.e. contains about 21% oxygen.) FIRE SIMULATOR also estimates the oxygen concentration in the smoke layer (See paragraph 7 of this chapter.) If the

oxygen in the smoke layer remains above a critical value, FIRE SIMULATOR assumes that the plume can complete the combustion of the available fuel. Conversely, if the oxygen level in the smoke drops below that critical value, combustion is limited to that supportable by the air entrained by the portion of the fire plume below the smoke layer.

(1) Limiting value for oxygen concentration required for combustion in smoke layer.

The limiting value is based on the temperature of the smoke gases as follows.

$$O_s = [(T_{fo} - T_s)/(T_{fo} - T_0)][O_{L1} - O_{L2}] + O_{L2} \quad (76)$$

where  $O_s$  = Limiting value of oxygen concentration required for combustion in the smoke layer  
 $T_{fo}$  = Designated flashover temperature (In degrees C)  
 $T_s$  = Smoke layer temperature (In degrees C)  
 $T_0$  = Room temperature (Assumed by FIRE SIMULATOR to be 21 C)  
 $O_{L1}$  = Minimum oxygen required for combustion near room temperature. (User input, default value 10%)  
 $O_{L2}$  = Minimum oxygen required for combustion near flashover temperature (User input, default value 2%)

(2) Oxygen entrained in portion of fire plume below the smoke layer.

The report of Heskestad, Engineering Relations for Fire Plumes, [28] was used as the source for these entrainment equations. A multi-step procedure is used as follows.

(a) Estimate effective fire diameter.

$$D = ((m_f/m''_f)/\pi)^{1/2}/2 \quad (77)$$

where  $D$  = Effective diameter of fire  
 $m_f$  = Mass burning rate  
 $m''_f$  = Mass burning rate per unit area (This value has a default rate based on the mass rate needed to produce 100 BTU/ft<sup>2</sup>-sec))

(b) Calculate a virtual source for the plume.

$$z_0 = -1.02D + 0.083q_p^{2/5} \quad (78)$$

where  $z_0$  = Position of virtual source (m above fire surface.)  
 $D$  = Effective diameter of fire (m)  
 $q_p$  = Actual rate of heat released by fire (kW)

(c) Calculate flame length

$$L = -1.02D + 0.23q_p^{2/5} \quad (79)$$

where  $L$  = Flame length (m above fire)

(d) Estimate height of reacting portion of plume.

This is estimated as the point where the temperature rise is 500°C above ambient.

$$z_1 = z_0 + (0.166q_c^{2/5}) \quad (80)$$

where  $z_1$  = Point in plume where temperature rise is 500°C above ambient.

(e) Estimate entrainment into smoke plume when height of smoke layer is less than  $z_1$ .

$$m_e = 0.0054q_c z / (0.166q_c^{2/5} + z_0) \quad (81)$$

where  $m_e$  = Mass of entrained air (kg/s)  
 $z$  = Distance from top of fire to bottom of smoke layer (m)

(f) Estimate entrainment into smoke plume when height of smoke layer is greater than  $z_1$ .

$$m_e = 0.071q_c^{1/3} (z - z_0)^{5/3} [1 + 0.026q_c (z - z_0)^{-5/3}] \quad (82)$$

(g) Calculate ability of entrained air to support combustion.

This equation is taken from the oxygen consumption relationship reported by Huggett [27]. The consumption of 1 kg of air results in the production of 3,000kJ of energy.

$$q_{en} = 3000m_e \quad (83)$$

where  $q_{en}$  = Amount of energy production that can be supported by the air entrained below the smoke layer (kW)

FIRE SIMULATOR imposes this limitation only if the level of oxygen in the smoke layer is less than or equal to  $O_s$ , described above.

#### 5.5 CALCULATION OF RESPONSE OF HEAT ACTUATED DEVICES (SPRINKLERS AND FIXED TEMPERATURE HEAT DETECTORS.)

The equations used to estimate the response of heat actuated devices in a room have been developed from the work of Evans [16] and Alpert [15]. The specific programing of the equations for this segment was provided by David Stroup [12].

The process is two phase.

a. Phase 1. Determining the virtual source and rate of heat release of a pseudo plume.

The phase 2 equations estimate the response of the heat actuated device to the hot ceiling jet. The correlations used in those equations assume that the plume producing the jet will entrain air that is at room temperature. In a room small enough to accumulate a layer of hot gases prior to response of the device some of the entrainment in the plume will consist of the hot gas mixture in the smoke layer. This can increase the temperature and velocity of the ceiling jet. The phase 1 equations developed by Evans[16] produce the elevation and rate of heat release of a pseudo plume that approximates the actual ceiling jet conditions when those revised values are entered as the data source terms in the phase 2 equations. This is a constantly changing relationship and is recalculated at each iteration of the computations. The specific equations used in phase 1 are

$$Q^*_1 = q_p / (P_0 c_0 T_0 g^{1/2} z^{5/2}) \quad (84)$$

where  $Q^*_1$  = A dimensionless value used in subsequent calculations  
 $q_p$  = Actual rate of heat released in room by the fire (kW)  
 $P_0$  = Density of air at ambient temperatures (1.1768 kg/m<sup>3</sup>)  
 $c_0$  = Specific heat of air (1.004 kJ/kg-K)  
 $T_0$  = Room temperature (Assumed by FIRE SIMULATOR to be 294 K)  
 $g$  = Acceleration of gravity (9.8 m/s<sup>2</sup>)  
 $z$  = Distance from top of fire to bottom of smoke layer

$$Q^*_2 = [([1 + (C_T Q^*_1)^{2/3}]) / (E_{TA} C_T)] - (1/C_T)]^{2/3} \quad (85)$$

where  $Q^*_2$  = A dimensionless value used in subsequent calculations  
 $C_T$  = 9.115 (A time constant proposed by Evans [16])  
 $E_{TA}$  = Ratio of absolute values of smoke temperature to ambient temperature ( $T_s/T_0$ )

$$z_{1x} = ([1/Q^*_2]^{1/3} [(E_{TA} - 1)(b_p + 1) + (E_{TA} C_T Q^*_2)^{2/3}]) E_{TA} Q^*_1 C_T^{2/5} z_{1y} \quad (86)$$

where  $z_{1x}$  = Incremental change in pseudo smoke level this iteration  
 $b_p$  = 0.913 (Characteristic width of plume, proposed by Evans[16])  
 $z_{1y}$  = Pseudo smoke level at previous iteration

$$q_2 = Q^*_2 P_0 c_0 T_0 g^{1/2} z_{1y}^{5/2} \quad (87)$$

where  $q_2$  = Pseudo rate of energy release reflecting entrainment of heated gases into fire plume (kW).

$$h_2 = h_1 + z_{1x} - z \quad (88)$$

where  $h_2$  = Pseudo distance from fire to ceiling reflecting entrainment of heated gasses into fire plume

$h_1$  = Actual distance from fire to ceiling

$z$  = Actual distance from fire to smoke layer

b. Calculations used to estimate the response of heat actuated devices (using the values derived above for  $q_2$  and  $h_2$ .)

$$R_h = r/h_2 \quad (89)$$

where  $R_h$  = Ratio of radial distance from center line of fire plume to position of heat actuated device to the pseudo height of the ceiling

$r$  = radial distance from center line of plume to device

If  $R_h < 0.18$

$$D_T = 6.18 \quad (90)$$

If  $R_h \geq 0.18$

$$D_T = 1.97R_h^{-2/3} \quad (91)$$

where  $D_T$  = A derived relationship used in subsequent calculations  
The values shown are for distances in m and temperatures in K

$$T_j = D_T / [c_0^2 p_0^2 g h_2^5 / (T_s q_2^2)]^{1/3} + T_s \quad (92)$$

where  $T_j$  = Temperature of ceiling jet at position of heat actuated device

If  $R_h < 0.15$

$$D_U = 3.16 \quad (93)$$

If  $R_h \geq 0.15$

$$D_U = 0.65R_h^{-5/6} \quad (94)$$

where  $D_U$  = A derived relationship used in subsequent calculations  
The values shown are for distances in m and temperatures in K



$$U_M = D_U / [c_0 T_s P_0 h_2 / (g q_2)]^{1/3} \quad (95)$$

where  $U_M$  = Velocity of ceiling jet at position of heat actuated device (m/s)

$$T = R_{ti} / U_M^{1/2} \quad (96)$$

where  $T$  = Heat transfer time constant  
 $R_{ti}$  = Response time index of heat actuated device

$$T_L = \{ (T_{jy} - T_{Ly}) (1 - e^{-t'/T}) + (T_j - T_{jy})^T [e^{-t'/T} + (1/T) - 1] \} + T_{Ly} \quad (97)$$

where  $T_L$  = Temperature of heat actuated element  
 $T_{Ly}$  = Temperature of heat actuated element at previous time increment in calculation  
 $T_{jy}$  = Temperature of ceiling jet at previous time increment in calculation  
 $e$  = Natural log base  
 $t'$  = Time increment used (In FIRE SIMULATOR  $t' = 1$ )

When  $T_L$  equals the temperature rating of the heat actuated device, the device is considered to be actuated.

## 6. CALCULATIONS FOR ESTIMATING RESPONSE OF SMOKE DETECTORS.

The equations for estimating the response of smoke detectors are identical to those for estimating the response of heat detectors. In the case of smoke detectors the value of  $R_{ti}$  is set at 1 and the value of  $T_L$  is set at a low temperature. (The default value for smoke detectors in FIRE SIMULATOR is 93°F, 34°C).

## 7. CALCULATION FOR ESTIMATING O<sub>2</sub> CONCENTRATION IN SMOKE LAYER.

As previously referenced, the estimation of oxygen concentration in the smoke layer is based on the relationship of energy production and use of oxygen. As described by Huggett [27], about one gram of oxygen is consumed for each 13 kJ of energy produced. There is a slight variation between individual fuels. FIRE SIMULATOR ignores this variation and uses 13 kJ/g as the universal value. At each one second time increment the concentration of O<sub>2</sub> is calculated. FIRE SIMULATOR considers the smoke layer in the room as a control volume. The mass of O<sub>2</sub> in the volume at the start of a one second time step is calculated. To this is added the mass inflow of O<sub>2</sub> during that second. The outflow of O<sub>2</sub> in the mass flow through any vent openings or extracted by any HVAC system during this same second is deducted. Also in any second when burning is in a ventilation limited mode FIRE SIMULATOR assumes that there is no O<sub>2</sub> inflowing into the smoke layer. The equations for O<sub>2</sub> concentration are as follows.

$$m_{in} = .23\Delta z A \rho_s - q\Delta t / 13000 \quad (98)$$

where  $m_{in}$  = Mass gain of  $O_2$  as the result of the inflow of  $O_2$  entrained in the fire plume and not consumed by combustion during the current 1 second iteration of FIRE SIMULATOR. (kg)

$\Delta z$  = FIRE SIMULATOR calculated additional descent of the smoke layer in current second of fire simulation, not adjusted for any vented mass (m). The value of  $\Delta z$  is derived as set forth in equations 1, 6 and 7. In FIRE SIMULATOR the value of LC (heat loss factor) in equation 6 is calculated for each 1 second iteration as described in paragraph 3 of this chapter and the value of QT (dimensionless rate of heat release) is determined by the user specified rate of heat release as adjusted by the equations described in paragraph 4 of this chapter.

A = Room area ( $m^2$ ). The expression  $\Delta z A \rho_s$  describes the mass flow entrained in the fire plume as it enters the smoke layer.

q = Rate of heat release (kW).

$\rho_s$  = Density of smoke layer ( $kg/m^3$ ).

$\Delta t$  = time increment (set at 1 second in FIRE SIMULATOR)

$$m_{out} = O_2 Q \rho_s \Delta t \quad (99)$$

where  $m_{out}$  = Mass loss of  $O_2$  as the result of out flow of  $O_2$  in the gases vented through openings during the current 1 second iteration of FIRE SIMULATOR.

Q = Volume outflow rate ( $m^3/s$ ) determined by equation 62 or 63 as determined by the criteria in paragraph 2.c. of this chapter.

$$m_s = O_2 V \rho_s \quad (100)$$

where  $m_s$  = Mass of oxygen in smoke layer at start of time step (kg)

$O_2$  = Mass fraction of oxygen in smoke.

V = Volume of smoke layer at start of current 1 second iteration of FIRE SIMULATOR. ( $m^3$ )

$$m_n = m_{in} + m_s - m_{out} \quad (101)$$

where  $m_n$  = Mass of oxygen in smoke at end of current 1 second iteration of FIRE SIMULATOR. This approach assumes that the density of the smoke layer is constant during the 1 second iteration. This is not actually true any time the smoke

temperature changes during that second. The induced error is, however, considered slight. (kg)

$$O2_f = m_n / (V\rho_s) \quad (102)$$

where  $O2_f$  = Mass fraction of oxygen in the smoke layer.

$$O2_z = 2100/23m_n \quad (103)$$

where  $O2\%$  = Percent by volume of oxygen in the smoke layer.

#### 8. CALCULATIONS FOR ESTIMATING CO AND CO<sub>2</sub> CONCENTRATION IN SMOKE LAYER.

The calculation of both CO and CO<sub>2</sub> are based on the assumption that the overwhelming mass of the volume concentration that is not oxygen or water vapor is a combination of CO and CO<sub>2</sub>. FIRE SIMULATOR further assumes that the ratio of oxygen available for combustion to the pyrolyzed products available to burn determines the proportioning of the production of CO and CO<sub>2</sub>.

a. Calculation of the volume portion being produced that is a combination of CO and CO<sub>2</sub>. (i.e The sum of the CO and CO<sub>2</sub> concentrations by volume.)

$$c_r = (100 - N_2 - O_2)/2[1 + (0.6(1 - (H_c - 17000)/17000))] \quad (104)$$

where  $N_2$  = Volume portion that is nitrogen (assumed to be 79%)  
 $c_r$  = Volume portion that is the combination of CO and CO<sub>2</sub>  
 $O_2$  = Oxygen content as derived in equation (103)  
 $H_c$  = Heat of combustion (kJ/g)

#### b. Determining CO/CO<sub>2</sub> ratio.

FIRE SIMULATOR assumes two different levels for the CO/CO<sub>2</sub> ratio. The lower ratio being assumed in conditions of excess oxygen, the higher being assumed when the available oxygen is insufficient to consume all of the pyrolyzed fuel. The determination is based on the calculations of combustion limits due to limited oxygen availability covered in paragraph 4 of this chapter. If the oxygen is shown to be sufficient to burn all the pyrolyzed fuel the lower CO/CO<sub>2</sub> ratio is used. If not the higher ratio is used.

#### c. Rate of CO and CO<sub>2</sub> production.

$$co_{in} = c_r x_r q / H_c \quad (105)$$

and

$$co_{2in} = c_r (1 - x_r) q / H_c \quad (106)$$

where  $co_{in}$  = Mass flow rate of CO into smoke layer  
 $co_{2in}$  = Mass flow rate of CO<sub>2</sub> into smoke layer  
 $x_r$  = CO/CO<sub>2</sub> ratio  
 $q$  = Rate of heat release (within room)  
 $H_c$  = Heat of combustion

#### d. CO and CO<sub>2</sub> concentration in smoke layer.

Then given the rate of CO and CO<sub>2</sub> production, the calculation of the concentration of CO and CO<sub>2</sub> in the smoke layer is done in the same manner as oxygen concentration in paragraph 7, above, adjusted for the molecular weight of these species.

#### 5.9 ESTIMATING VISION DISTANCE IN THE SMOKE LAYER.

FIRE SIMULATOR equates visibility as the distance at which the smoke blocks 95% of the light from a source. FIRE SIMULATOR does not consider any irritating effects that might impose vision problems on a person whose eyes were actually in the smoke layer.

The calculations used are derived from the work of Mulholland [30]. The calculations estimate the maximum vision distance as a function of the specific extinction coefficient ( $e_c$ ) of the material being burned. A value of 1 m<sup>2</sup>/g for  $e_c$  means that if the smoke produced by burning 1g of that fuel were contained within a cross sectional area of 1m<sup>2</sup> the layer would block 65% of the light incident on that surface. For values of  $e_c$  less than 1 the light stopping ability would be proportionally less and the smoke would have to be confined within a proportionally smaller cross section to produce the same 65% reduction in light transmission. The procedure for this determination is identical to that used for determining CO or CO<sub>2</sub> concentrations, described in the preceding section, except that the proportionally ratio of product produced to product burned ( $m_p$ ) is 1.0. With this data the equation used is

$$V_s = 3/(e_c M_p) \quad (107)$$

where  $V_s$  = Distance (m) at which light is reduced by 95%  
 $e_c$  = Specific extinction coefficient (m<sup>2</sup>/g)  
 $M_p$  = Mass burned per m<sup>3</sup> of smoke volume produced

The 95% reduction in light transmission equated to vision distance in FIRE SIMULATOR occurs at the point where  $e_c$  is 1/3 m<sup>2</sup>/g. The calculation requires a determination of the total mass burned less a factor for that vented through any opening.

#### ACKNOWLEDGEMENTS

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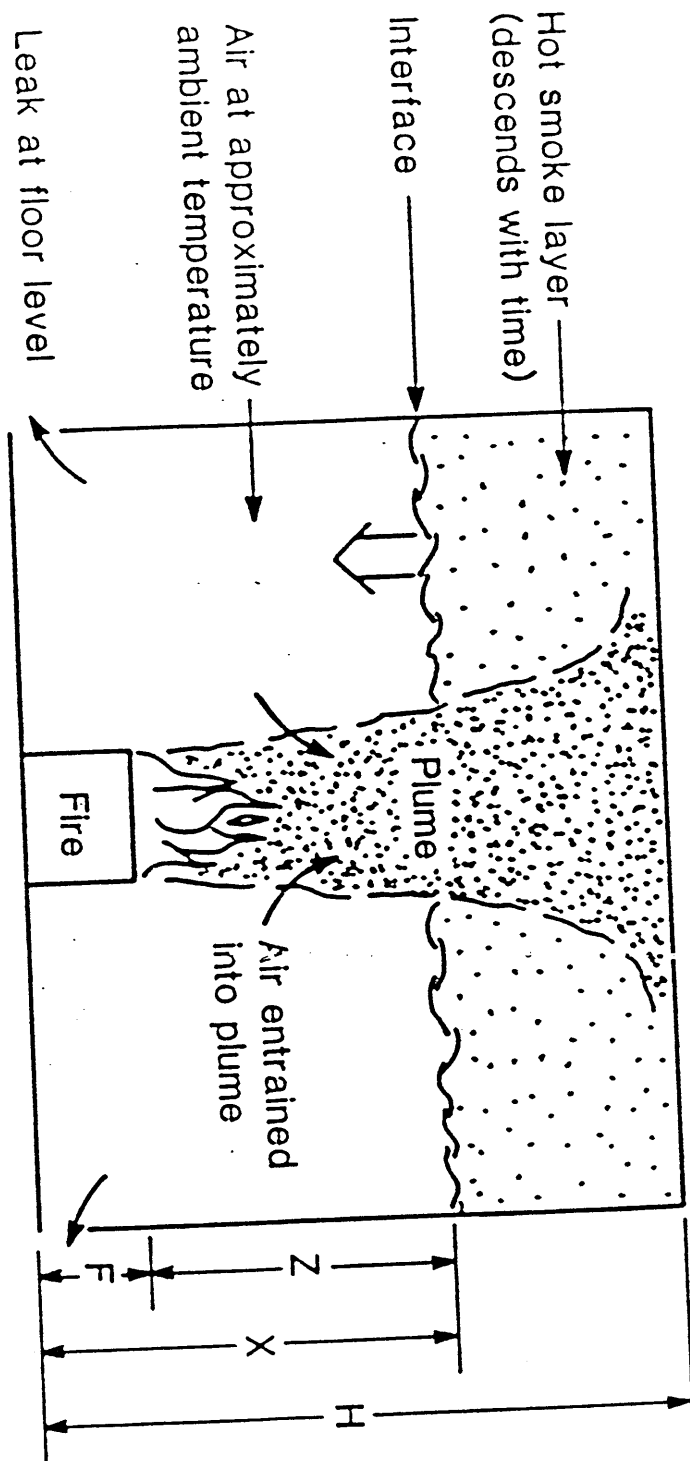


Figure 1. Schematic of fire phenomena



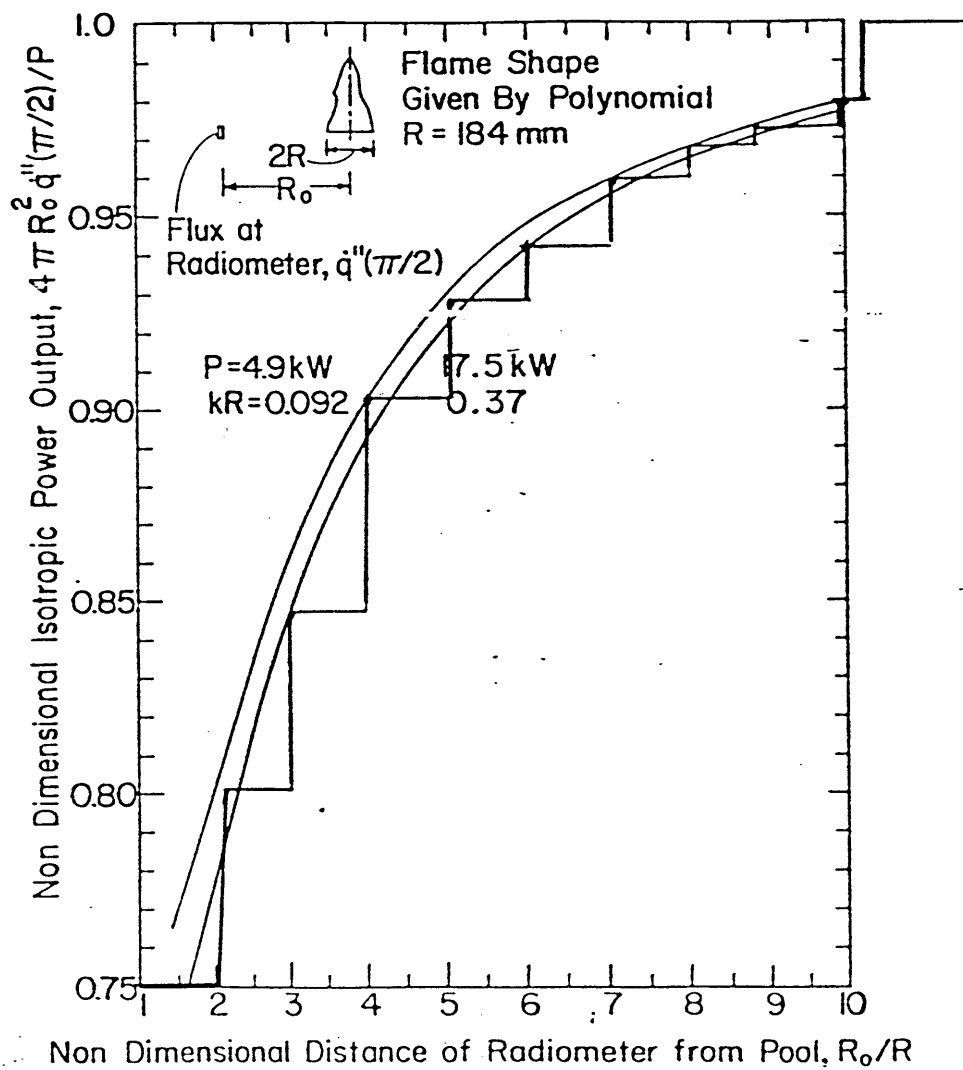


Figure 2. Comparison of radiation adjustment curves present by Modak [20] and adjustment values used in FPETOOL. (The smooth curves are from Modak [20]; the step function is that used in FPETOOL.)



## Appendix A

### Comparison of results from FIRE SIMULATOR to test data.

The purpose of this appendix is to provide the user with a selection of comparisons between the results produced by FIRE SIMULATOR and the conditions observed in several well instrumented tests. It is expected that these comparisons will assist the user in understanding the general range of accuracy that can be expected from the estimates produced by FIRE SIMULATOR.

#### 1. Test Selections.

The tests used were selected on the basis of:

- a. Tests that were well instrumented supported by a report detailing the data taken.
- b. The data included mass loss data for at least the pre-flashover phase of the test fire.
- c. The several tests used, in combination, represented significantly different conditions, testing different aspects of FIRE SIMULATOR.

There is a sparsity of test data meeting the above criteria. Most of the tests fitting the above criteria have been conducted under the direction of the Center for Fire Research. The tests selected are:

a. Product Research Committee Test 19-W-4-1/4 (PRC-19) [1,2]. This test involved the burning of 4 wood cribs in a 51 ft.<sup>2</sup> (4.75 m<sup>2</sup>) room with a ceiling height of 7.9 ft. (2.4m.) There was a single room opening 6 ft. (1.82m) high and 7.5 inches (204 mm) wide, with the sill at floor level. The investigators selected this narrow opening to produce near maximum temperatures possible without producing flashover or ventilation limited burning. The FIRE SIMULATOR input screen and a minimum set of output data are included as figure A-1.

b. Test B1 of the Fire Tests of the Prototype 19F3 Navy Firefighter Trainers (NAV-TRAINER) [3]. The test was one of a series of acceptance tests for a burn chamber designed to train U.S. Navy personnel in fighting ship board fires. The space is of steel construction, 21 ft. (6.4 m) high, having an area of 890 ft.<sup>2</sup> (83 m<sup>2</sup>.) The fire was provided by a propane burner located 5 ft. above the bottom of the test chamber. There is approximately 27 ft.<sup>2</sup> (2.5 m<sup>2</sup>) of room opening, all located near the base of the facility, below the level of the burner. In addition there is a fan-powered ventilation system venting at an estimated 83 air changes per hour (approximately 26,000 cfm or 12.2 m<sup>3</sup>/S). The propane burner produces about 10MW. The FIRE SIMULATOR input screen and a minimum set of output data are included as figure A-2.

c. Sharon 2 simulation of a townhouse fire (SHARON-2) [4]. The burn room conditions in a two-story 6-room test facility are examined. The test simulated the conditions in an actual fire. The burn room was 8 ft. (2.4m) high with an area of 96 ft.<sup>2</sup> (8.9 m<sup>2</sup>), located on the first floor of the test facility. There was an opening from the burn room to the remainder of the building 6.66 ft. (2 m) high and 2.5 ft. (0.76 m) wide. At the start of the test, the only vent opening in the facility was a window opening in a second floor room. That opening was 6 in. (0.15 m) high and 3 ft. (0.9 m) high. The sill of this opening being about 12 ft. (3.6 m) above the burn room floor. When flashover was determined by the test director a panel was removed from the exterior wall of the burn room, simulating the breakage of glass windows. This opening had height of 5 ft. (1.5 m) above the floor with a window sill 0.9 ft. (0.27 m) above that same floor. The post-flashover opening was 2.5 ft. (0.76 m) wide. The fuel consisted of a combination of wood cribs and sheets of untreated plywood. The FIRE SIMULATOR input screen and a minimum set of output data are included as figure A-3.

## 2. Analysis of Product Research Committee Test PRC-19.

The data obtained from the test and the results obtained by FIRE SIMULATOR (and the FIREFORM procedure UPPER LAYER TEMPERATURE) are shown in figure A-4 through A-8.

a. Figure A-4 is a plot of the temperatures recorded by a thermocouple tree in the test room. The thermocouples were evenly spaced at 6 in. (0.15 m) intervals from the floor to the ceiling. Every fourth thermocouple is plotted on figure A-4. The compression of the upper thermocouple readings demonstrates a hot upper layer. The spread in reported temperature, however, points out that the single temperature reported by FIRE SIMULATOR is an approximation and the actual conditions will vary from that predicted. The plots in this figure do demonstrate a reasonably defined upper and lower layer. There were, however, several temperature traces (in the range of about 0.5 to 1.0 meters above the floor) showing a middle zone, not accounted for in two zone models such as FIRE SIMULATOR. It appears that a modest gradient rather than a sharp interface separating the zones existed. Such variations from the assumptions of the zone model should be expected in most instances.

b. Figure A-5 is a plot of temperatures developed by running the data described for this test in FIRE SIMULATOR and UPPER LAYER TEMPERATURE. The open diamonds plot the estimated average upper layer temperature derived from the thermocouple readings above the temperature inflection zone. This level of approximation by FPETOOL routines probably represents as good a level accuracy as can be expected from these routines.

c. Figure A-6 is a plot of the depth of the smoke layer calculated by FIRE SIMULATOR. The open diamonds plot the temperature inflection point. This point is derived from a plot of the temperature distribution on a single thermocouple tree at the time indicated and establish-

ing the point where the tangent of the line connecting these points is closest to horizontal.

d. Figure A-7 is a plot of the FIRE SIMULATOR calculation of oxygen content in the smoke layer and the minimum level of oxygen measured by the investigators through a sampling in the smoke layer during the test.

e. Figure A-8 plots the mass flow through the vent (door opening) as calculated by FIRE SIMULATOR in comparison to that observed by the investigators. In this case two vent flow rates inflow and out flow are plotted. Both were calculated. The difference in these measured values shows experiential variance. It is felt that the out flow is more nearly accurate. This because the hotter out flowing gases have a higher velocity and tend to register better on the bi-directional probes used in the experiment.

### 3. Analysis of Test B1 of the Fire Tests of the Prototype 19F3 Navy Firefighter Trainers (NAV-TRAINER).

The data obtained from the test and the results obtained by FIRE SIMULATOR are shown in figures A-9 through A-12. This test is felt to present a significant challenge to FIRE SIMULATOR. The combination of a very large fire, steel construction, and a high fan-powered ventilation rate present conditions widely different from a simple furniture fire in a conventional sized room. As noted in chapters 2 and 5, FIRE SIMULATOR is expected to produce less accurate prediction where thermally thin lining materials (such as steel) are involved. The relative closeness of the calculated to the measured results shown in figures A-10 through A-12 is more surprising than the degree of variance shown.

a. Figure A-9 plots the measured temperatures recorded by a thermocouple tree extending from the 5-foot (1.5 m) level to near the top of the facility. The positions shown for the location of the temperature plots are shown in terms of meters above that level. To compare these results with those shown in figures A-10 through A-12 add 1.5 m to each indicated level. As with the previous test, the results show an upper layer hot zone that in itself has a temperature gradient, a low level cool area, and an intermediate transition zone.

b. Figure A-10 plots the average upper layer temperature prediction of FIRE SIMULATOR against the maximum average temperature as derived from the test data. In this case FIRE SIMULATOR over predicts temperature by about 100° C (about 200° F.) It is possible that this represents the inaccuracies in FIRE SIMULATOR in calculating heat transfer involving thermally thin lining materials.

c. Figure A-11 compares the calculated drop in the smoke level with that derived from the temperature data recorded. Since the observers could not view the interior of the test facility, the smoke layer level was derived from the test data, reflecting the gradients shown in figure A-9.

d. Figure A-12 compares the calculated oxygen concentration in the smoke layer with the measured level. In this case the measured minimum oxygen level was about 18% while FIRE SIMULATOR estimates about 10%.

4. Analysis of Sharon 2 simulation of a townhouse fire (SHARON-2). In the test as well as FIRE SIMULATOR calculations, the oxygen supply in the portion of the townhouse test facility outside the burn room dropped below that required to support combustion of the fuel vented through that opening (i.e. 5% in the test and near 3% calculated by FIRE SIMULATOR.) The open window on the second floor was however a factor. To estimate this, the FIREFORM procedure SMOKE FLOW THROUGH AN OPENING was used to estimate the resultant added air provided for combustion. To do this it was estimated that the temperature near the open window was 300°F (about 150°C). The result indicated an air movement of about 1000 cfm (0.5 cms.) This equates to approximately 1 air change in the burn room each 45 seconds (80 air changes per hour.) In the FIRE SIMULATION calculation this was simulated by simulating an HVAC system moving 80 air changes per hour.

This test also passed through the flashover stage. FIRE SIMULATOR calculates the post flashover burning rates as a function of the projected exposed burning rate. The fuel in this test was treated as a single burning mass and the projected areas were estimated as approximately 35% of the horizontal surfaces and 25% of the vertical projections of all 4 walls. Figure A-13 shows the smoke layer temperature calculated by FIRE SIMULATOR as well as the plot of both the highest reporting thermocouple in the burn room and the average temperature derived from the measured temperature array.

#### REFERENCES CITED IN APPENDIX A

1. Quintiere, J. G. and McCaffery, B. J.; The Burning of Wood and Plastic Cribs in an Enclosure - Volume I; Report NBSIR 80-2045; National Institute of Standards and Technology (formerly National Bureau of Standards); Gaithersburg, MD; 1980.
2. Quintiere, J. G., McCaffery, B. J., and Harkleroad, M.; The Burning of Wood and Plastic Cribs in an Enclosure - Volume II; Report NBSIR 80-2054; National Institute of Standards and Technology (formerly National Bureau of Standards); Gaithersburg, MD; 1980.
3. Levine, R. S. and Rinkinen, W.; Report of Test, Fire Tests of the Prototype 19F3 Navy Fire Fighter Trainers; National Institute of Standards and Technology; Gaithersburg, MD; to be published.
4. Levine, R. S. and Nelson, H. E.; Full Scale Simulation of a Fatal Fire and Comparison of Results with Two Multiroom Models; National Institute of Standards & Technology; Gaithersburg, MD; to be published

RUN TITLE: PRC19-W-4-1/4 ROOM TEST OF 4 PINE CRIBS - 1/4 OPEN DOOR  
 ROOM: HGT: 7.91 ft 2.41 m AREA: 51.15 ft<sup>2</sup> 4.75 m<sup>2</sup>  
 CEILING: 100 %PRC-MARN 0.75 in. WALLS: 100 %PRC-MARN 0.75 in.  
 WALL OPENING: 6.00 ft. HIGH 0.62 ft. WIDE WITH A 0.00 ft. HIGH SILL  
 NO HVAC DEFINED  
 NO SPRINKLER (HEAT DETECTOR) PRESENT  
 NO SMOKE DETECTOR PRESENT  
 FIRE HEIGHT: 0.6 ft 0.2 m FLASHOVER AT 1112.00  $\frac{1}{2}$ F ( 600.00  $\frac{1}{2}$ C)  
 MINIMUM OXYGEN REQUIRED FOR BURNING IS 10.0 TO 1.0 % BY VOL.  
 HEAT OF COMBUSTION: 5824.00 [btu/lb] (13000.00 [kj/kg])  
 SPECIFIC EXTINCTION COEFFICIENT: 0.10  
 MAX INT ENERGY LOSS FRACT: 0.950  
 RADIANT ENERGY FRACTION (FROM FLAME): 0.350  
 FIRE IS FIRE DATA FILE PRC19.FIR  
 4 sugar pine cribs-fire height 0.18m  
 >>>>>>>>>> DO YOU WANT TO CHANGE ANY OF YOUR ENTRIES? (Y/N)

---

FIRE SIMULATOR  
[VER 1.00]

---

RUN TITLE: PRC19-W-4-1/4 ROOM TEST OF 4 PINE CRIBS - 1/4 OPEN DOOR  
 INPUT DATA USED FOR RUN OF 07-27-1990 15:03:57  
 DATA FILE USED: PRC19A.IN AS OF 07/27/90 15:03:34  
 ASCII FILE NAME: PRC19A.PRN  
 HEAT OF COMBUSTION: 5824 BTU/lb 13000 Kj/kg  
 SPECIFIC EXTINCTION COEFFICIENT: .1  
 FLASHOVER TEMPERATURE: 1112 F 600 C  
 OXYGEN STARVATION THRESHOLDS: 10 % by vol @ 70 F 1 % by vol @ 1112 F  
 RADIANT ENERGY FRACTION (FROM FLAME): .35  
 MAXIMUM PRE FLASHOVER ENERGY LOSS FACTOR: .95  
 THERE IS NO SPRINKLER/HEAT DETECTOR DEFINED  
 THERE IS NO SMOKE DETECTOR DEFINED  
 DESCRIPTION OF INITIAL OUTSIDE OPENING:  
 HEIGHT OF OPENING: 6 ft 1.829268 m  
 WIDTH OF OPENING: .62336 ft .1900488 m  
 HEIGHT OF SILL ABOVE FLOOR: 0 ft 0 m  
 SPACIAL DIMENSIONS OF ROOM:  
 ROOM FLOOR AREA: 51.1544 ft<sup>2</sup> 4.752244 m<sup>2</sup>  
 ROOM WALL PERIMETER: 28.6089 ft 8.722226 m  
 ROOM IS NOT RECTANGULAR  
 DESCRIPTION OF CEILING MATERIALS:

Figure A-1 (Page 1 of 2) Input Screen and Print Output from PRC19

100 % PRC-MARN .75 IN 19.05 mm

DESCRIPTION OF WALL MATERIALS:

100 % PRC-MARN .75 IN 19.05 mm

THERE IS NO HVAC DEFINED

FIRE HEIGHT: 0.59 ft. 0.18 m

4 sugar pine cribs-fire height 0.18m

FIRE DESCRIPTION USED CAME FROM FILEFILE: PRC19.FIR

TIME	-----TEMP-----		-----LAYER-----		-----FIRE-----	
sec	F	C	ft	m	kW	BTU/sec
0.0	70.0	21.1	7.9	2.4	0.1	0.1
VISION DISTANCE (smoke layer) = 3000.00 m 9840.00 ft						
SMOKE GASES : OXYGEN = 21.0 % : CO = 0.0000 : CO2 = 0.0000 %						
SMOKE VENT RATE IS 0 cfm 0.00 csm						
ENTHALPY (Heat content) 0 btu/sec 0 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						
200.0	879.8	471.0	2.5	0.8	354.4	336.1
VISION DISTANCE (smoke layer) = 2.83 m 9.27 ft						
SMOKE GASES : OXYGEN = 7.4 % : CO = 0.0174 : CO2 = 10.8572 %						
SMOKE VENT RATE IS 1043 cfm 0.49 csm						
ENTHALPY (Heat content) 98 btu/sec 103 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						
400.0	850.5	454.7	2.5	0.8	276.6	262.4
VISION DISTANCE (smoke layer) = 2.82 m 9.25 ft						
SMOKE GASES : OXYGEN = 10.1 % : CO = 0.0124 : CO2 = 8.6865 %						
SMOKE VENT RATE IS 1017 cfm 0.48 csm						
ENTHALPY (Heat content) 94 btu/sec 99 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						
501.0	772.5	411.4	2.6	0.8	194.3	184.3
VISION DISTANCE (smoke layer) = 2.80 m 9.18 ft						
SMOKE GASES : OXYGEN = 12.8 % : CO = 0.0082 : CO2 = 6.5838 %						
SMOKE VENT RATE IS 948 cfm 0.45 csm						
ENTHALPY (Heat content) 84 btu/sec 89 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						

=====RUN COMPLETED=====



RUN TITLE: NAVY TRAINER 8.3.89--- 83 Air changes of stp gas/hour  
 ROOM: HGT: 20.97 ft 6.39 m AREA: 889.40 ft» 82.63 m»  
 CEILING: 100 %STEEL2 1.97 in. WALLS: 100 %STEEL2 1.97 in.  
 WALL OPENING: 0.82 ft. HIGH 32.81 ft. WIDE WITH A 0.10 ft. HIGH SILL  
 HVAC IS DEFINED WITH 82.75 AIR CHANGES/Hr AT 100.00% COMBUSTION EFFICIENCY  
 NO SPRINKLER (HEAT DETECTOR) PRESENT  
 NO SMOKE DETECTOR PRESENT  
 FIRE HEIGHT: 4.9 ft 1.5 m FLASHOVER AT 1112.00 1/2 F ( 600.00 1/2 C)  
 MINIMUM OXYGEN REQUIRED FOR BURNING IS 10.0 TO 1.0 % BY VOL. :  
 HEAT OF COMBUSTION: 20608.00 [btu/lb] (46000.00 [kj/kg])  
 SPECIFIC EXTINCTION COEFFICIENT: 0.10  
 MAX INT ENERGY LOSS FRACT: 0.950  
 RADIANT ENERGY FRACTION (FROM FLAME): 0.350  
 FIRE IS FIRE DATA FILE NAVY.FIR  
 NO ADDITIONAL DESCRIPTION PROVIDED  
 >>>>>>>>>> DO YOU WANT TO CHANGE ANY OF YOUR ENTRIES? (Y/N)

---

FIRE SIMULATOR  
[VER 1.00]

---

RUN TITLE: NAVY TRAINER 8.3.89--- 83 Air changes of stp gas/hour

INPUT DATA USED FOR RUN OF 08-01-1990 07:11:51

DATA FILE USED: NAB1E.IN AS OF 08/01/90 07:10:52

ASCII FILE NAME: NAB1E.PRN

HEAT OF COMBUSTION: 20608 BTU/lb 46000 Kj/kg  
 SPECIFIC EXTINCTION COEFFICIENT: .1  
 FLASHOVER TEMPERATURE: 1112 F 600 C  
 OXYGEN STARVATION THRESHOLDS: 10 % by vol @ 70 F 1 % by vol @ 1112 F  
 RADIANT ENERGY FRACTION (FROM FLAME): .35  
 MAXIMUM PRE FLASHOVER ENERGY LOSS FACTOR: .95

THERE IS NO SPRINKLER/HEAT DETECTOR DEFINED

THERE IS NO SMOKE DETECTOR DEFINED

DESCRIPTION OF INITIAL OUTSIDE OPENING:

HEIGHT OF OPENING: .8202 ft .250061 m  
 WIDTH OF OPENING: 32.8084 ft 10.00256 m  
 HEIGHT OF SILL ABOVE FLOOR: .1 ft 3.048781E-02 m

SPACIAL DIMENSIONS OF ROOM:

ROOM FLOOR AREA: 889.4015 ft^2 82.6254 m^2  
 ROOM WALL PERIMETER: 119.2913 ft 36.3693 m  
 ROOM IS NOT RECTANGULAR

DESCRIPTION OF CEILING MATERIALS:

Figure A-2 (Page 1 of 2) Input Screen and Print Output from NAV-TRAINER

100 % STEEL2 1.9685 IN 49.9999 mm

DESCRIPTION OF WALL MATERIALS:

100 % STEEL2 1.9685 IN 49.9999 mm

DESCRIPTION OF HVAC:

COMBUSTION EFFICIENCY OF HVAC AIR: 100 %  
AIR CHANGES PER HOUR: 82.745

FIRE HEIGHT: 4.92 ft. 1.50 m

NO ADDITIONAL DESCRIPTION PROVIDED

FIRE DESCRIPTION USED CAME FROM FILEFILE: NAVY.FIR

TIME	-----TEMP-----		-----LAYER-----		-----FIRE-----	
sec	F	C	ft	m	kW	BTU/sec
0.0	70.0	21.1	21.0	6.4	0.1	0.1
VISION DISTANCE (smoke layer) = 3000.00 m 9840.00 ft						
SMOKE GASES : OXYGEN = 21.0 % : CO = 0.0000 : CO2 = 0.0000 %						
SMOKE VENT RATE IS 0 cfm 0.00 csm						
ENTHALPY (Heat content) 0 btu/sec 0 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						
50.0	867.0	463.9	10.0	3.1	10093.4	9573.6
VISION DISTANCE (smoke layer) = 1.89 m 6.20 ft						
SMOKE GASES : OXYGEN = 12.3 % : CO = 0.0094 : CO2 = 4.2696 %						
SMOKE VENT RATE IS 0 cfm 0.00 csm						
ENTHALPY (Heat content) 0 btu/sec 0 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						
100.0	864.0	462.2	10.4	3.2	10093.4	9573.6
VISION DISTANCE (smoke layer) = 0.94 m 3.09 ft						
SMOKE GASES : OXYGEN = 9.0 % : CO = 0.0217 : CO2 = 5.9899 %						
SMOKE VENT RATE IS 0 cfm 0.00 csm						
ENTHALPY (Heat content) 0 btu/sec 0 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						

=====RUN COMPLETED=====

Figure A-2 (Page 2 of 2)



100 % GYPSUM BOARD .5 IN 12.7 mm

DESCRIPTION OF WALL MATERIALS:

60 % GYPSUM BOARD .5 IN 12.7 mm

40 % PLYWOOD .5 IN 12.7 mm

THERE IS NO HVAC DEFINED

FIRE HEIGHT: 0.00 ft. 0.00 m

BURN RATES FROM SCALE DURING SHARON SIMULATION TEST IN TOWNHOUSE ON 9-22-88  
FIRE DESCRIPTION USED CAME FROM FILEFILE: SHARSIM.FIR

A HALT FLAG IS SET FOR TIME = 84 Sec

TIME	-----TEMP-----		-----LAYER-----		-----FIRE-----	
sec	F	C	ft	m	kW	BTU/sec
0.0	70.0	21.1	8.0	2.4	0.1	0.1
VISION DISTANCE (smoke layer) = 3000.00 m 9840.00 ft						
SMOKE GASES : OXYGEN = 21.0 % : CO = 0.0000 : CO2 = 0.0000 %						
SMOKE VENT RATE IS 0 cfm 0.00 csm						
ENTHALPY (Heat content) 0 btu/sec 0 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						
83.0	1113.4	600.8	3.4	1.0	2071.6	1964.9
VISION DISTANCE (smoke layer) = 1.43 m 4.68 ft						
SMOKE GASES : OXYGEN = 8.4 % : CO = 0.0205 : CO2 = 9.9033 %						
SMOKE VENT RATE IS 4162 cfm 1.97 csm						
ENTHALPY (Heat content) 425 btu/sec 448 kW						
INSIDE FLOW OF UNBURNED FUEL POTENTIAL 0 BTU/SEC 0 kW						

UPPER LEVEL TEMP. INDICATES THAT FLASHOVER HAS PROBABLY OCCURRED BY 83 SEC.

POST FLASHOVER

COMBUSTION EFFICIENCY	100.00	
HEAT OF COMBUSTION	17857.1KJ/kg	8000BTU/S
BASE HEAT OF GASIFICATION	2.0KJ/kg	1BTU/S
FUEL LOAD	5.00LBS/ft^2	24.41kg/M^2
% BURNABLE =	100.00	
HORIZONTAL COMB. SURFACE (%)	25.00	
VERTICAL COMB. SURFACE (%)	35.00	
HORZ. COMB. SURF. > 1/4 IN. (%)	25.00	
VERT. COMB. SURF. > 1/4 IN. (%)	35.00	
HORZ. COMB. SURF > 1 IN. (%)	10.00	
VERT. COMB. SURF > 1 IN. (%)	10.00	
DURATION (SEC) =	861	
INSIDE OPENING IS	0.00ft X 0.00ft	0.000m X 0.000m
OUTSIDE OPENING IS	2.50ft X 5.00ft	0.762m X 1.524m

-----  
PROGRAM HALTED AT 84 SECONDS DUE TO

-----  
TIME DEPENDANT STOP SPECIFIED BY USER.

NO INSIDE OPENING DEFINED

NO OUTSIDE OPENING DEFINED

Figure A-3 (Part 2 of 3)

```

HVAC DEFINED AS COMBUSTION EFFICIENCY FOR AIR: 100    AIR CHANGES/Hr: 80
      84.0    1100.9    593.8    2.6    0.8    1297.9    1231.0
VISION DISTANCE (smoke layer) =    1.63 m    5.34 ft
SMOKE GASES : OXYGEN =    8.2 % : CO =    0.0649 : CO2 =    9.9724 %
SMOKE VENT RATE IS    0 cfm    0.00 csm
ENTHALPY (Heat content)    0 btu/sec    0 kW
INSIDE FLOW OF UNBURNED FUEL POTENTIAL    0 BTU/SEC    0 kW

      601.0    1550.6    843.6    2.5    0.8    2406.9    2283.0
VISION DISTANCE (smoke layer) =    0.01 m    0.02 ft
SMOKE GASES : OXYGEN =    0.0 % : CO =    4.9447 : CO2 =    11.5376 %
SMOKE VENT RATE IS    0 cfm    0.00 csm
ENTHALPY (Heat content)    0 btu/sec    0 kW
INSIDE FLOW OF UNBURNED FUEL POTENTIAL    0 BTU/SEC    0 kW

```

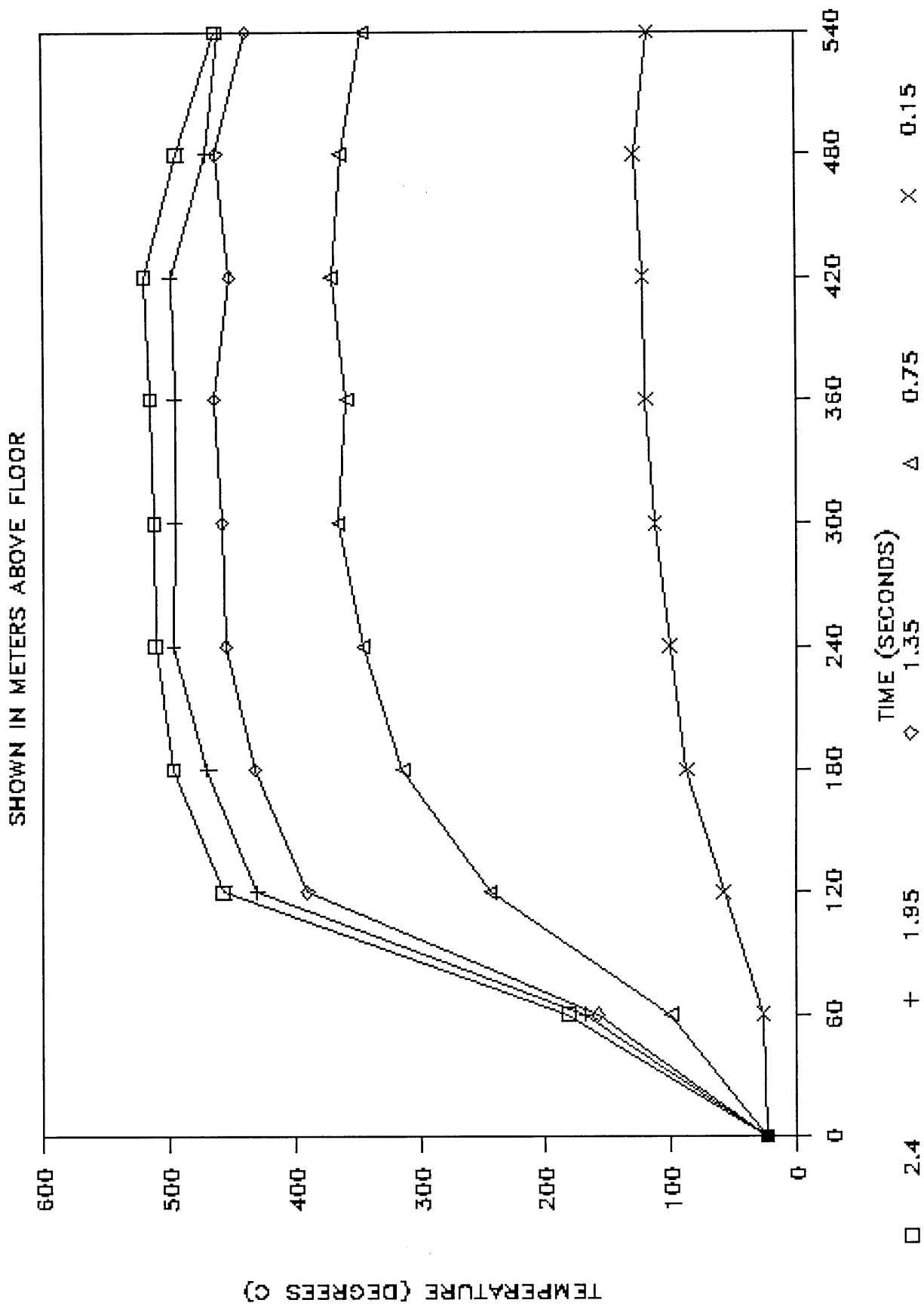
```

=====RUN COMPLETED=====

```

Figure A-3 (Part 3 of 3)

# FIGURE A-4 - PRC19 - MEASURED TEMP.



# FIGURE A-5 - PRC19 - TEMPERATURE

FIRE SIMULATOR - FIREFORM AND MEASURED

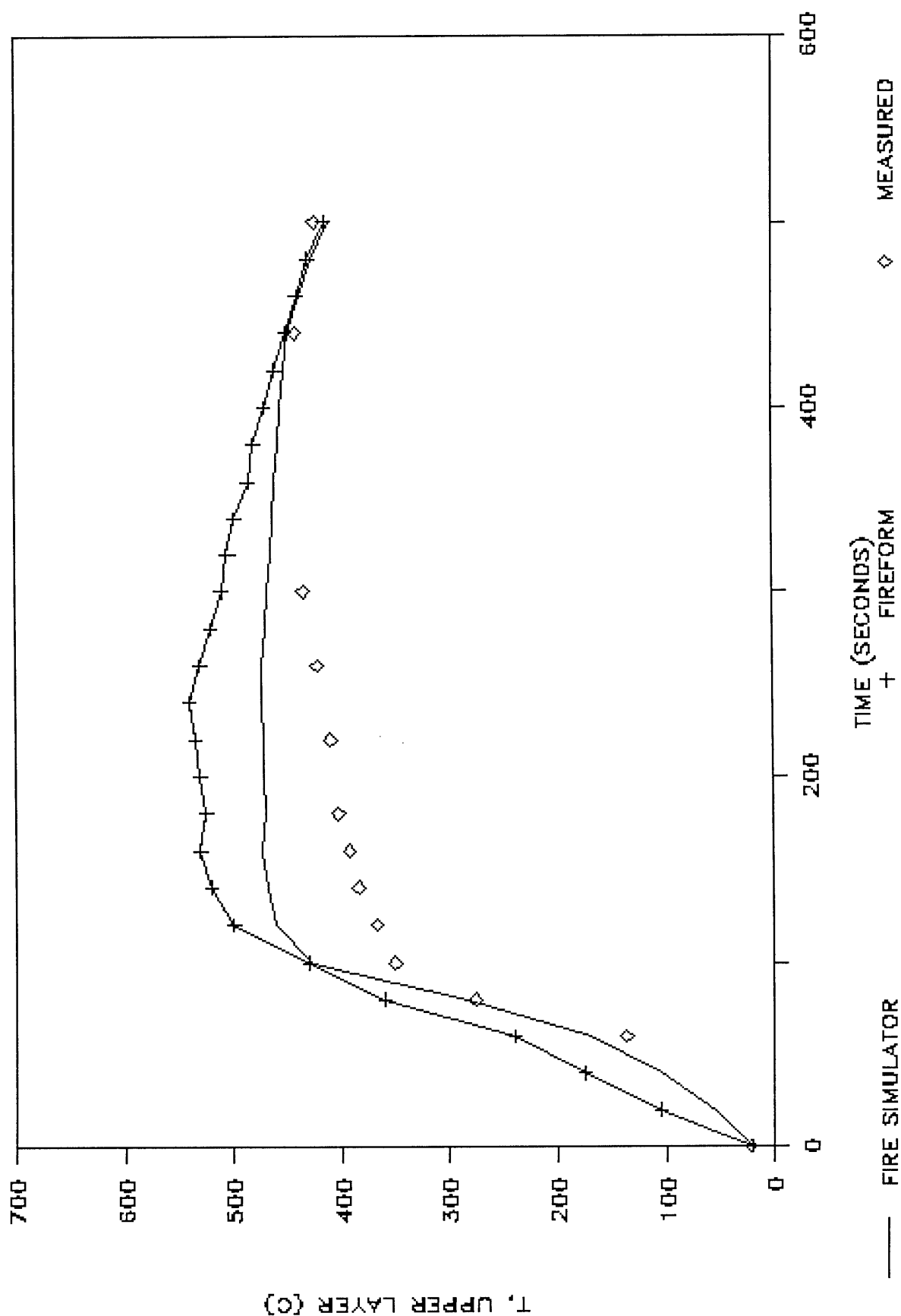
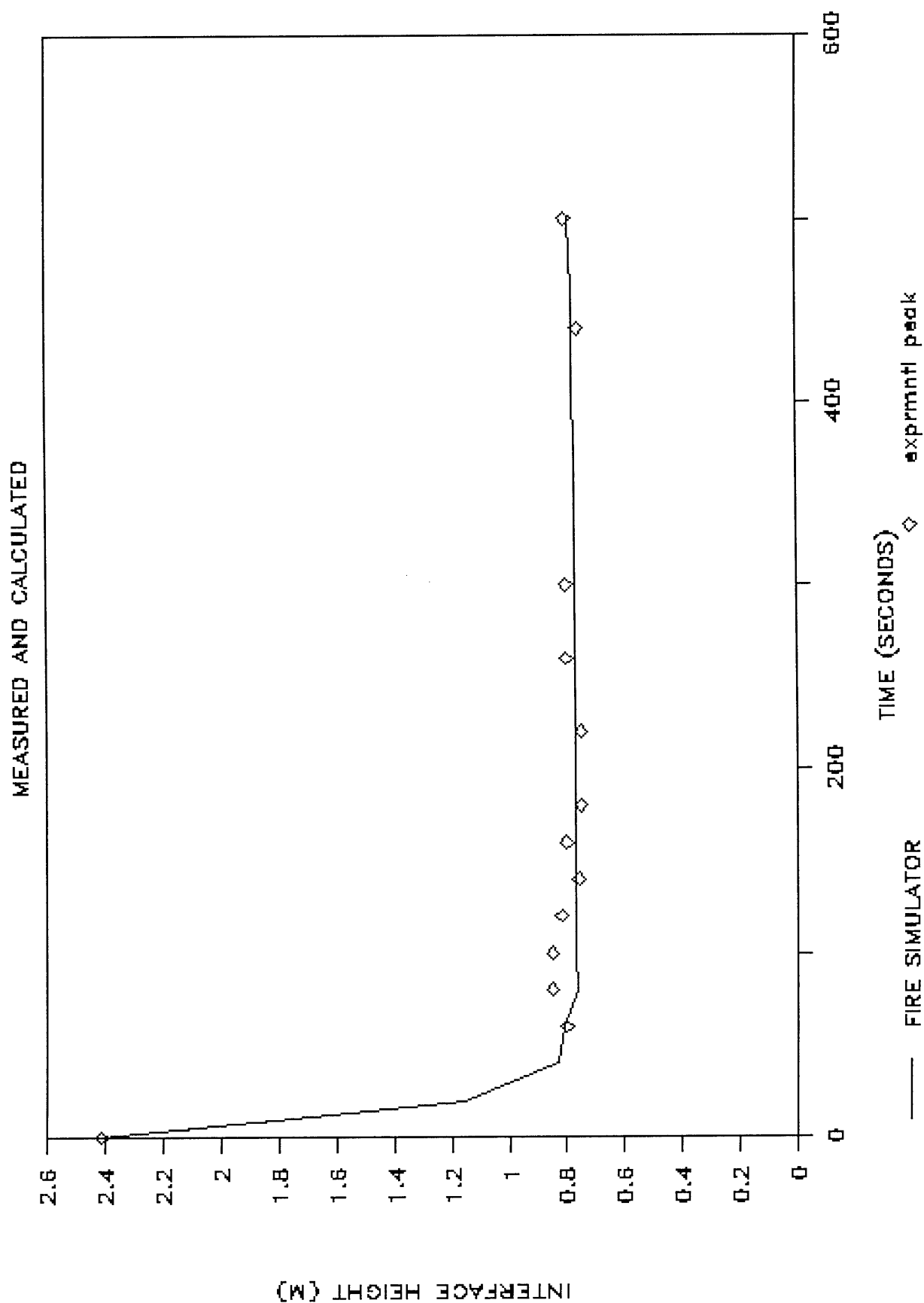
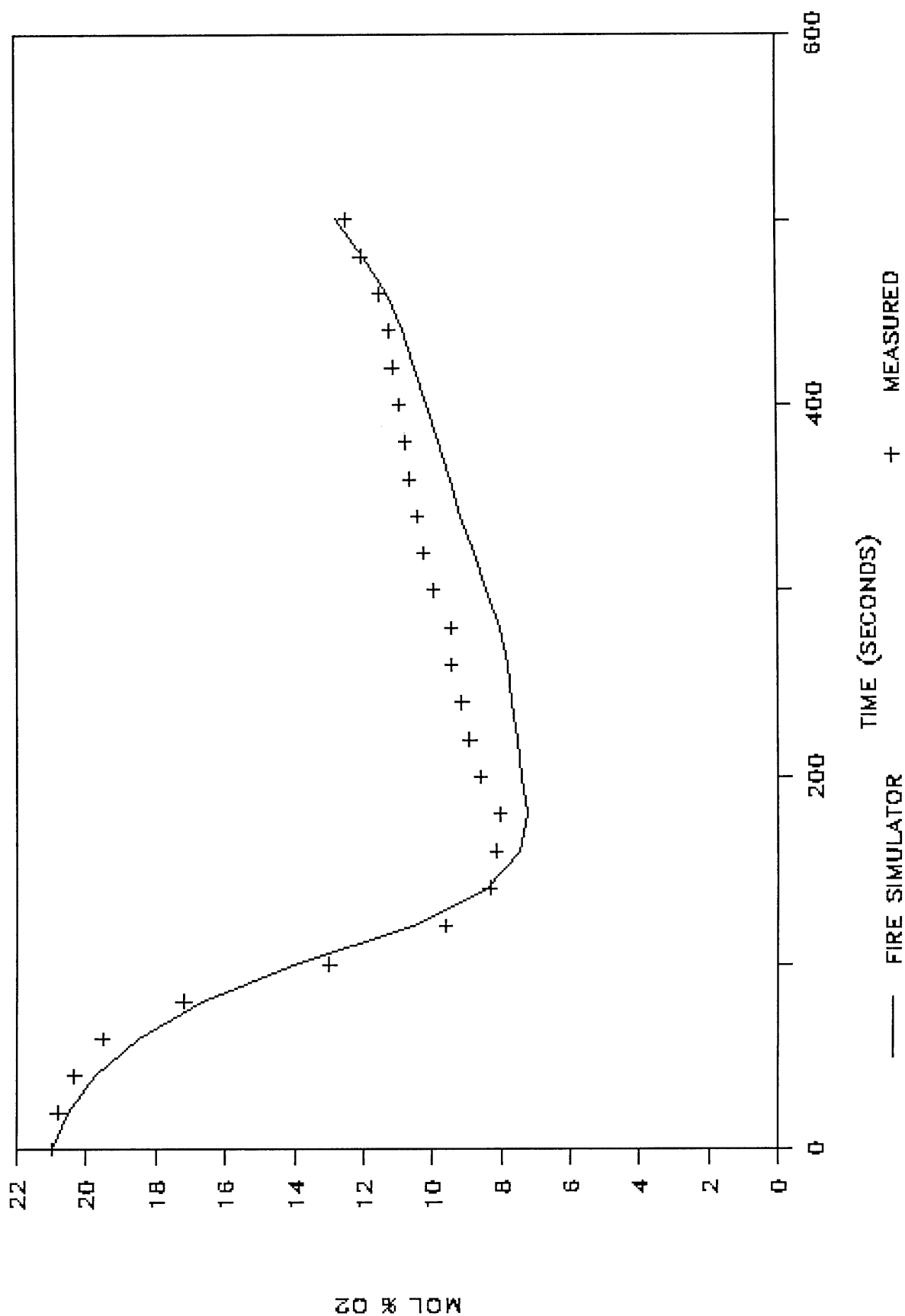


FIGURE A-6 - PRC19 - INTERFACE LEVEL





# FIGURE A-7 - PRC19 - OXYGEN MEASURED AND CALCULATED



# FIGURE A-8 - PRC19 - VENT FLOWS

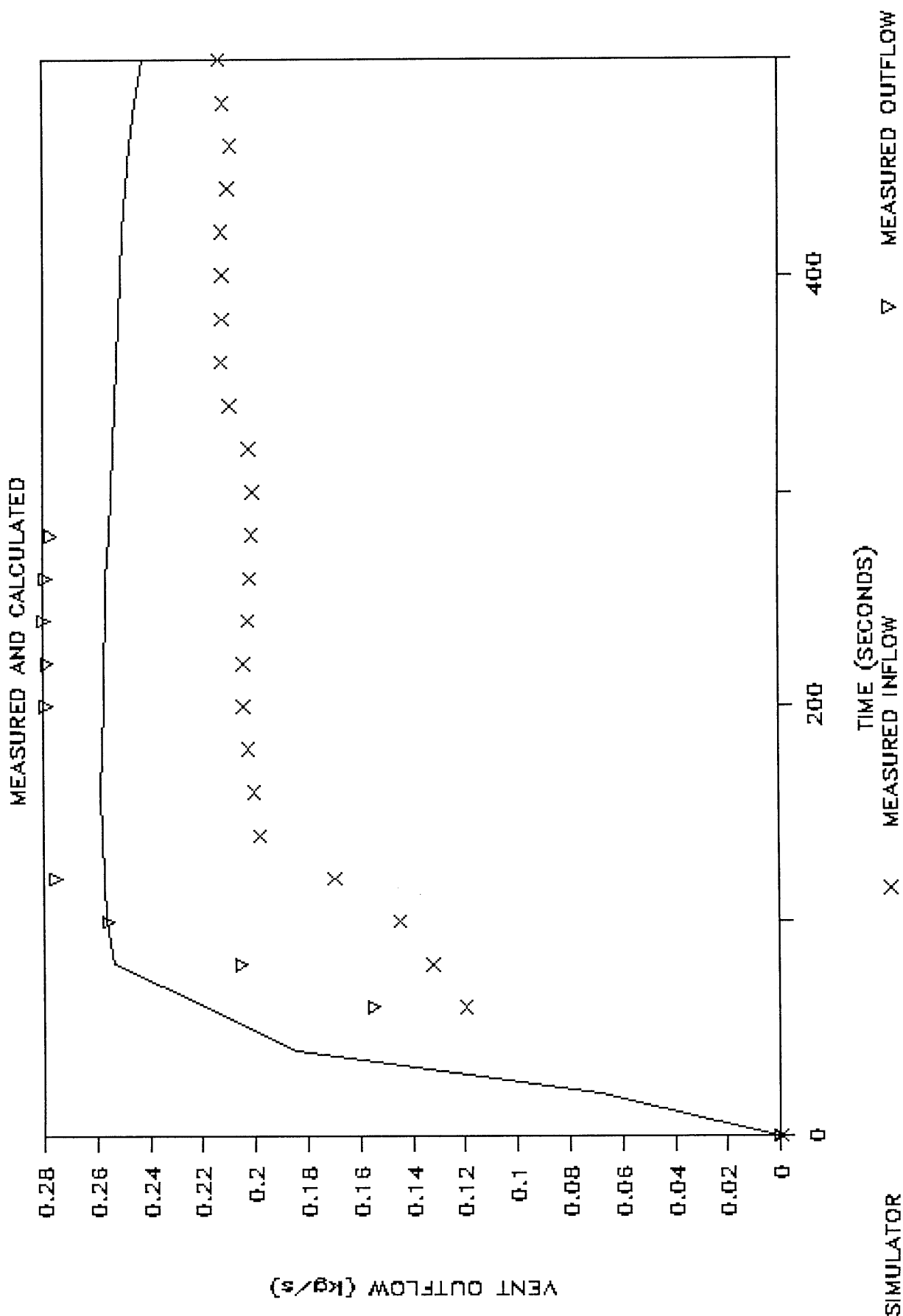


FIGURE A-9 - NAV - TRAINER - MEASURED TEMP.

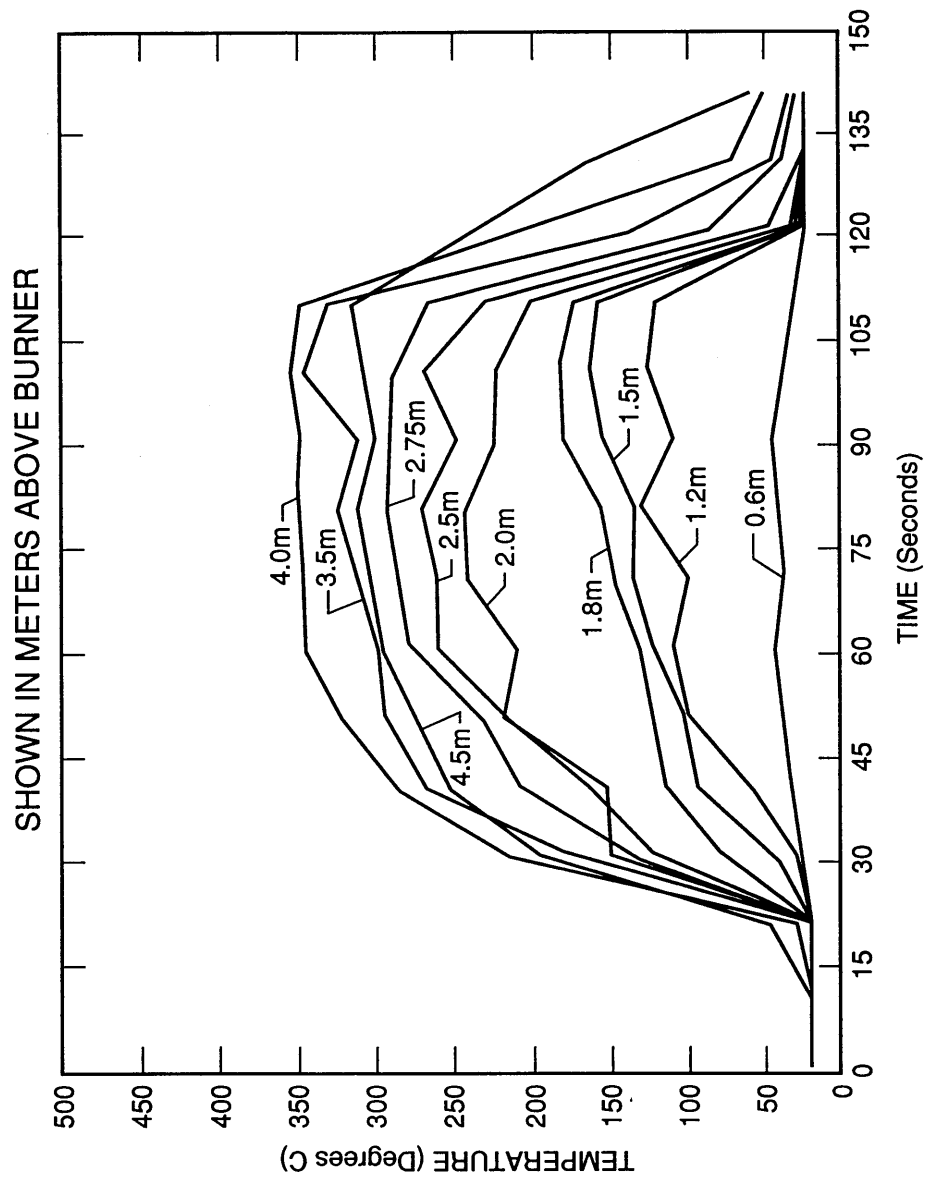


FIGURE A-10 - NAV-TRAINER -TEMPERATURE

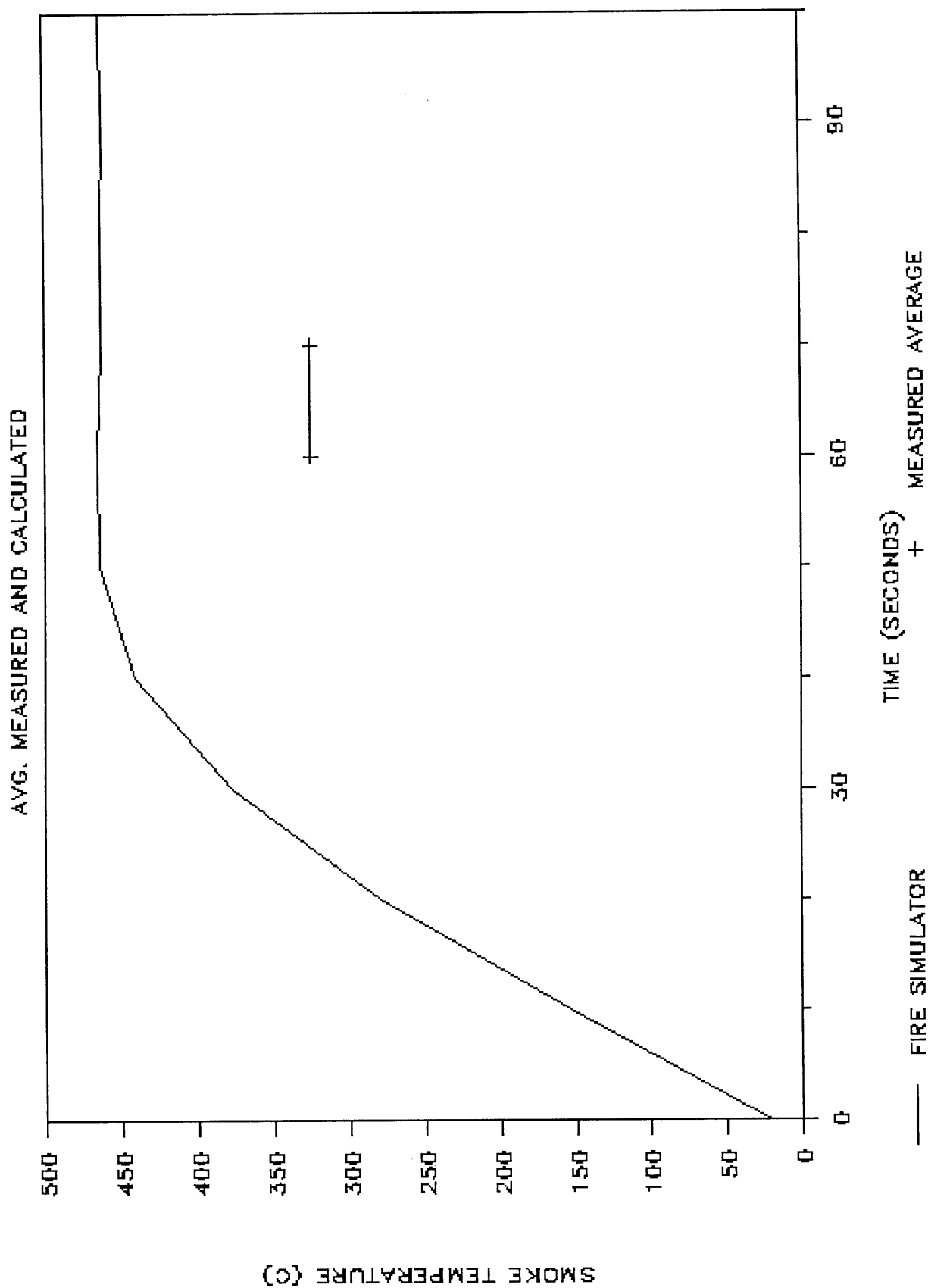
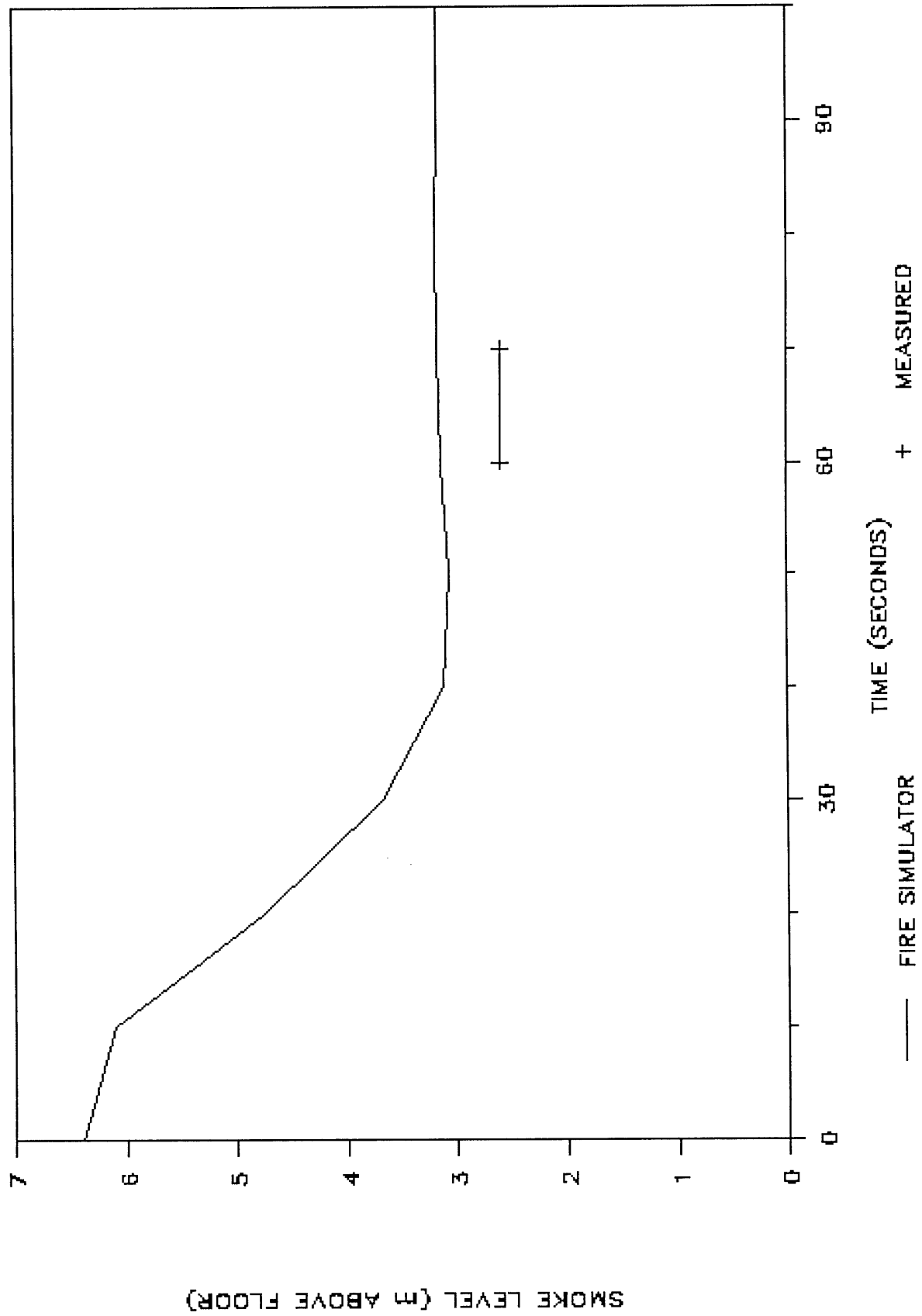
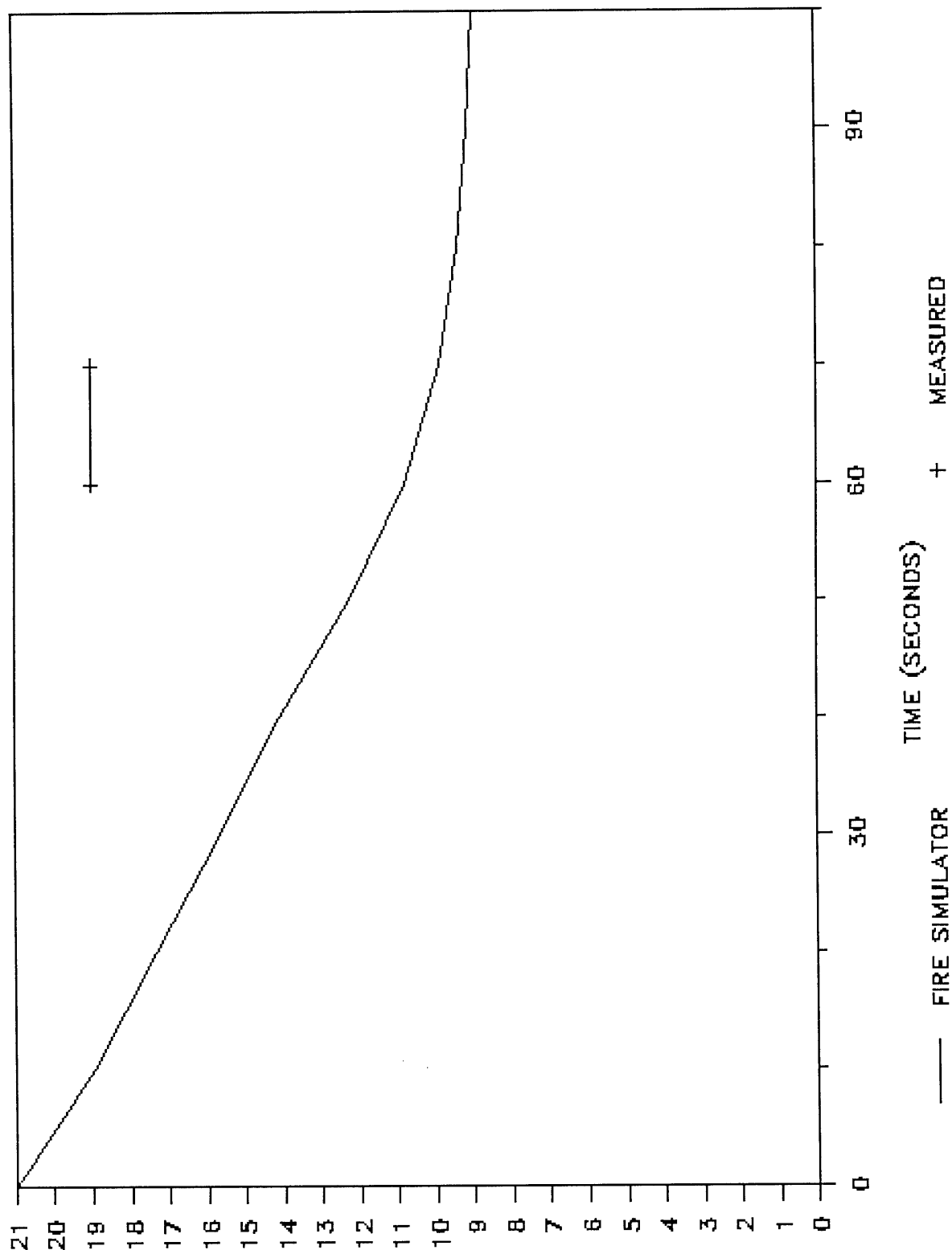


FIGURE A-11 — NAV-TRAINER — INTERFACE  
MEASURED AND CALCULATED

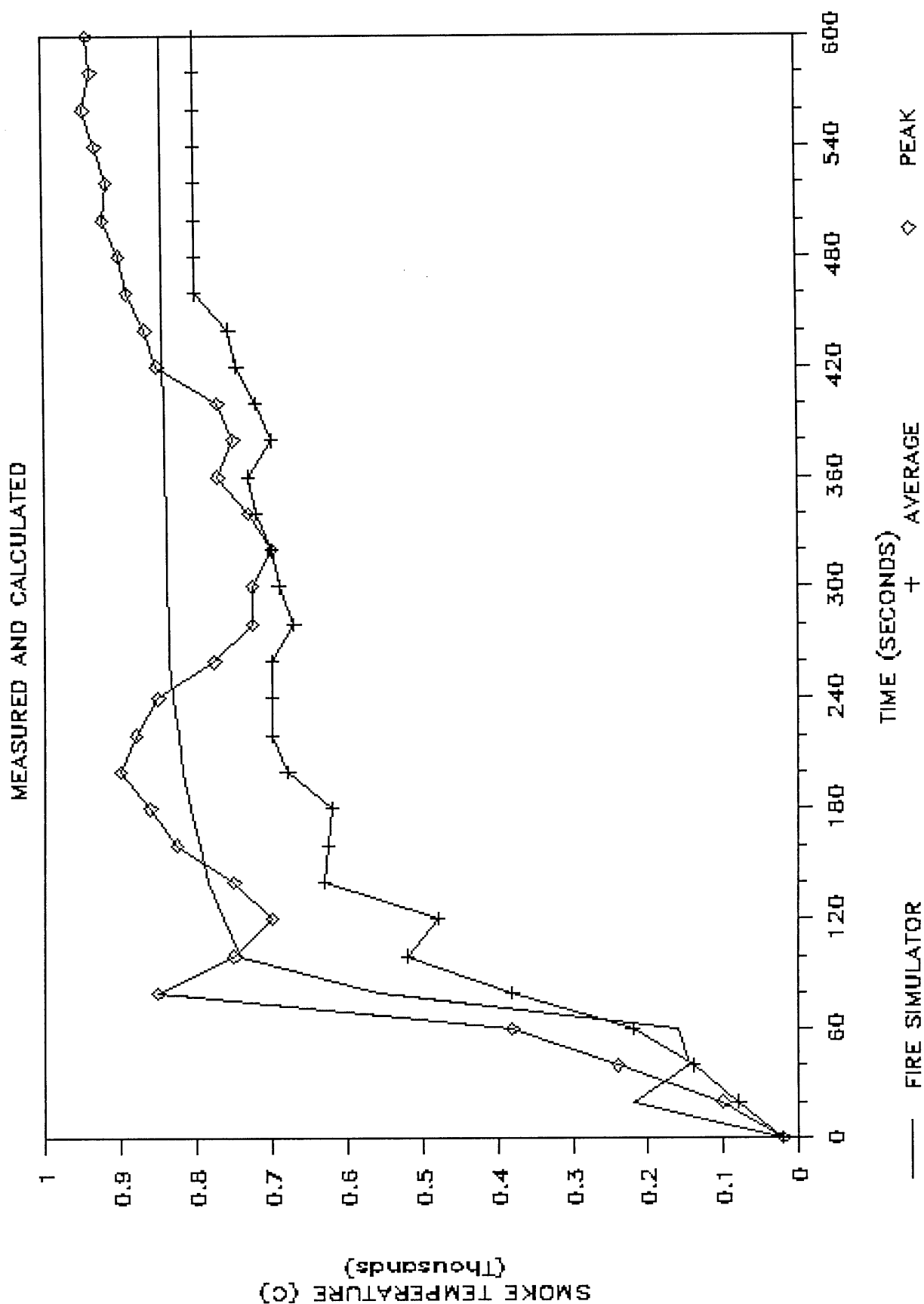


# FIGURE A-12 - NAV-TRAINER - OXYGEN

MEASURED AND CALCULATED



# FIGURE A-13 SHARON-2 TEMPERATURE







## APPENDIX B

### INSTRUCTION FOR ACCESS AND USE OF THE CFRBBS

(THE CENTER FOR FIRE RESEARCH COMPUTER BULLETIN BOARD)

**CFRBBS** is a public access computer bulletin board featuring computer programs developed by the Center for Fire Research. **CFRBBS** also contains information on **FIREDOC** and Center for Fire Research activities.

#### What you will find on **CFRBBS**

- Fire simulation programs developed at the Center for Fire Research (source programs and PC executables).  
For example, the latest versions of:  
ASCOS      ASET      ASET-B      CCFM      DETACT-QS      DETACT-T2  
EXITT      FAST      FIREFORM      FIRST      FPETOOL      LAVENT
- Information on **FIREDOC**, the Center for Fire Research bibliographic search system.
  - Password information
  - FIREDOC** Users Guide
  - FIREDOC** compatible communications package
- Information on upcoming activities at the Center for Fire Research.
  - Conferences
  - Seminars
  - Workshops
- A listing of the most recent year's reports from the Center for Fire Research.
- And more.

#### How to access **CFRBBS**

**CFRBBS** is designed for operation with IBM PC, PS/2 and compatible computers. **CFRBBS** is a one telephone line system, so please be patient.

Modem Telephone: (301) 921-6302

Hours: 24 hours a day 7 days a week in the unattended mode from Gaithersburg Maryland.

Baud Rate: 300, 1200, or 2400

Communications packages: compatible with most packages

Communications parameters: 8 data bits, no parity and one stop bit

Download protocols supported: Xmodem, Ymodem, Crxmodem or Kermit (to download programs)

Password: User created at signon

Fee: No connect fee, user pays for phone call

Contact: Doug Walton, the system operator at (301) 975-6872.

Operated by: The Center for Fire Research, National Institute of Standards and Technology,  
U.S. Department of Commerce, Gaithersburg, Maryland 20899

Programs for Personal Computers  
Developed by the  
Center For Fire Research  
National Institute of Standards and Technology

**ASCOS** (Analysis of Smoke Control Systems) is a program for steady air flow analysis of smoke control systems. This program can analyze any smoke control system that produces pressure differences with the intent of limiting smoke movement in building fire situations. The input consists of the outside and building temperatures, a description of the building flow network and the flows produced by the ventilation or smoke control system. The output consists of the steady state pressures and flows throughout the building. ASCOS was written in FORTRAN by J.H. Klote.

**ASET** (Available Safe Egress Time) is a program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows. ASET can be used to determine the time to the onset of hazardous conditions for both people and property. The required program inputs are the heat loss fractions, the height of the fire, criteria for hazard and detection, the room ceiling height, the room floor area, a heat release rate and (optional) species generation rate of the fire. The program outputs are the temperature, thickness and (optional) species concentration of the hot smoke layer as a function of time, and the time to hazard and detection. ASET can examine multiple cases in a single run. ASET was written in FORTRAN by L.Y. Cooper and D.W. Stroup.

**ASET-B** (Available Safe Egress Time - BASIC) is a program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows. ASET-B is a compact easy to run program which solves the same equations as ASET. The required program inputs are a heat loss fraction, the height of the fire, the room ceiling height, the room floor area, the maximum time for the simulation, and the rate of heat release of the fire. The program outputs are the temperature and thickness of the hot smoke layer as a function of time. ASET-B was written in BASIC by W.D. Walton.

**CCFM (version VENTS)** (Consolidated Compartment Fire Model version VENTS) is a two-layer zone-type compartment fire model computer code. It simulates conditions due to user-specified fires in a multi-room, multi-level facility. The required inputs are a description of room geometry and vent characteristics (up to 9 rooms, 20 vents), initial state of the inside and outside environment, and fire energy release rates as a functions of time (up to 20 fires). If simulation of concentrations of products of combustion is desired, then product release rates must also be specified (up to three products). Vents can be simple openings between adjacent spaces (natural vents) or fan/duct forced ventilation systems between arbitrary pairs of spaces (forced vents). For forced vents, flow rates and direction can be user-specified or included in the simulation by accounting for user-specified fan and duct characteristics. Wind and stack effects can be taken into account. The program outputs for each room are pressure at the floor, layer interface height, upper/lower layer temperature and (optionally) product concentrations. CCFM (version VENTS) is supported by four-part documentation: Part I - Physical Basis, L.Y. Cooper and G.P. Forney; Part II - Software Reference Guide, G.P. Forney and L.Y. Cooper; Part III - Catalog of Algorithms and Subroutines, L.Y. Cooper and G.P. Forney, Eds.; and Part IV - User Reference Guide, G.P. Forney, L.Y. Cooper, and W.F. Moss. CCFM (version VENTS) was written in FORTRAN by G.P. Forney and L.Y. Cooper.

**CCFMPLT** is a graphics program which runs in conjunction with CCFM. The results from CCFM are sent to a user specified data file at each prescribed time step. CCFMPLT plots this data on an IBM-PC compatible microcomputer and can optionally provide hardcopy output. CCFMPLT was written in FORTRAN by G.P. Forney.

EXITT is a discrete event simulation of occupant decisions and actions in a simulated fire. Before the simulation starts, the characteristics of a residence, a fire in that residence, and the occupants of the residence are entered into the computer. Based on a large set of decision rules, the occupants "make" decisions which are a function of the smoke conditions in the building, the characteristics and status of the occupants (including their capabilities), and the available travel routes. The occupants investigate the fire, alert and assist others, and evacuate the building. The simulation ends when all the occupants are either out of the building or are trapped by the smoke. EXITT was written in BASIC by Bernard Levin.

FAST (Fire And Smoke Transport) is a multi-room fire model which predicts the conditions within a structure resulting from a user specified fire. FAST version 18 can accommodate up to ten rooms with multiple openings between the rooms and to the outside. The required program inputs are the geometrical data describing the rooms and connections, the thermophysical properties of the ceiling, walls and floors, the fire as a rate of mass loss and the generation rates of the products of combustion. The program outputs are the temperature and thickness of, and species concentrations in, the hot upper layer and the cooler lower layer in each compartment. Also given are surface temperatures and heat transfer and mass flow rates. FAST was written in FORTRAN by W.W. Jones.

FASTPLOT is a graphing program which runs in conjunction with FAST. The results for FAST are dumped to a special data file after each prescribed time step. FASTPLOT has the capability to form a list of variables, read in their values at each time interval, list the values in tabular form, plot the values (hard copy or screen), and save the variables in a formatted file for use with other software. FASTPLOT is written in FORTRAN by W.W. Jones.

FAST\_IN is an interactive utility program which is used to create or edit an input file to be executed by the FAST model. FAST\_IN is written in FORTRAN by W.W. Jones.

FIREFORM (FIRE FORMulas) is a collection of 15 different fire related computational procedures based on established formulas. The subjects covered include smoke filling in a room, sprinkler/detector activation, smoke flow through (small) openings, temperatures and pressures developed by fires, flashover and fire severity predictions, fire propagation (in special cases), and simple egress estimation. FIREFORM was written in BASIC by H.E. NELSON.

FIRST (FIRE Simulation Technique) is the direct descendant of the HARVARD V program developed by Howard Emmons and Henri Mitler. The program predicts the development of a fire and the resulting conditions within a room, given a user-specified fire or user-specified ignition. It predicts the heating and possible ignition of up to three targets. The required program inputs are the geometrical data describing the rooms and openings, and the thermophysical properties of the ceiling, walls, burning fuel, and targets. The generation rate of soot must be specified, and the generation rates of other species may be specified. The fire may be entered either as a user-specified time-dependent mass loss rate or in terms of fundamental properties of the fuel. Among the program outputs are the temperature and thickness of, and species concentrations in, the hot upper layer and also in the cooler, lower layer in each compartment. Also given are surface temperatures, and heat transfer and mass flow rates. The FIRST program was written in FORTRAN and is maintained by Henri Mitler.

GRAPH is a graphics program which runs in conjunction with LAVENT. The results for LAVENT are sent to the data file, GRAPH.OUT, after each prescribed time step. GRAPH then allows the user to choose two sets of variables to be plotted on the screen and has the additional capability of hardcopy output. GRAPH was written in FORTRAN by William D. Davis.

LAVENT is a program developed to simulate the environment and the response of sprinkler links in compartment fires with draft curtains and fusible-link-actuated ceiling vents. The model used to calculate the heating of the fusible links includes the effects of the ceiling jet and the upper layer of hot gases beneath the ceiling. The required program inputs are the geometrical data describing the compartment, the thermophysical properties of the ceiling, the fire elevation, the time dependent energy release rate of the fire, the fire diameter or energy release rate per area of the fire, the ceiling vent area, the fusible link response-time-index (RTI) and fuse temperature, the fusible link positions along the ceiling, the link assignment to each ceiling vent, and the ambient temperature. A maximum of five ceiling vents and ten fusible links are permitted in the compartment. The program outputs are the temperature, mass and height of the hot upper layer, the temperature of each link, the ceiling jet temperature and velocity at each link, the radial temperature distribution along the interior surface of the ceiling, the radial distribution of the heat flux to the interior and exterior surfaces of the ceiling, the fuse time of each link, and the vent area that has been opened. LAVENT was written in FORTRAN by William D. Davis and Leonard Y. Cooper.

MASBANK is used to create and maintain a data base of materials and their fire properties for use by the FIRST program. MASBANK can accommodate 20 properties for up to 50 materials. The program has the capability to add, delete, change, alphabetize and view the material properties in the data bank. Material properties from MASBANK may be transferred directly into the FIRST program. MASBANK is written in FORTRAN.

The following compacted files are available on CFRBBS for IBM PC, XT, AT, PS/2 and compatible computers using DOS 2.0 or later:

DISKA01.ZIP (requires 105K free memory, a math coprocessor is recommended)

Contains the ASET source program in FORTRAN (modified for personal computers), a compiled version which can be run on computers without a FORTRAN compiler, a test case and a file with information on using the personal computer version of ASET

DISKA02.ZIP (requires 64K free memory)

Contains the ASET-B source program in BASIC, compiled versions of the program which can be run on computer without a BASIC compiler, a file with information on running the programs and the complete report on the ASET-B program.

DISKA03.ZIP (requires 190K free memory, a math coprocessor is recommended)

Contains the ASCOS source program in FORTRAN (modified for personal computers), a compiled version which can be run on computers without a FORTRAN compiler, several test cases and a file with information on using the personal computer version of ASCOS. The user should refer to the ASHRAE Smoke Control Manual (Klote, J.H. and Fothergill, J.W. "Design of Smoke Control Systems for Buildings" published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia) for program documentation and a description of the input data.

**DISKF06.ZIP** (requires 464K free memory, a math coprocessor is REQUIRED, DISKF01, DISKF02 and DISKF04 are REQUIRED, an EGA display is recommended)

Contains test case data files for the FAST program.

**DISKG01.ZIP** (requires 423K free memory, a math coprocessor is REQUIRED, an 80286 or 80386 computer is recommended)

Contains the a compiled version of the FIRST program which can be run on computers without a FORTRAN compiler and a file with information on using the personal computer version of FIRST

**DISKG02.ZIP** (requires 74K of free memory, a math coprocessor is REQUIRED)

Contains the MASBANK source program in FORTRAN (modified for personal computers), a compiled version which can be run on computers without a FORTRAN compiler, a test case, a file with information on using the personal computer version of MASBANK, a sample FIRST output file and a file describing the output label names for FIRST

**DISKG03.ZIP**

Contains the part 1 of the FIRST source program in FORTRAN (modified for personal computers).

**DISKG04.ZIP**

Contains the part 2 of the FIRST source program in FORTRAN (modified for personal computers).

**DISKL01.ZIP** (requires 261K free memory, a math coprocessor is REQUIRED, an 80286 or 80386 computer is recommended)

Contains the a compiled version of the LAVENT program which can be run on computers without a FORTRAN compiler and a file with the LAVENT user's guide.

**DISKL02.ZIP** (requires 259K of free memory, a math coprocessor is REQUIRED)

Contains the a compiled version of the GRAPH program for use with LAVENT

Note: Typical download time for these files is 30 minutes each at 1200 baud.

**DISKA06.ZIP** (requires 64K free memory)

Contains the EXITT source programs in BASIC, data files for sample cases and a report on the EXITT program.

**DISKA07.ZIP** (requires 64K free memory)

Contains the DETACT-QS and DETACT-T2 source programs in BASIC, the DETACT-T2 source program in FORTRAN, compiled versions of the programs which can be run on computer without a BASIC or FORTRAN compiler and file with information on running the programs.

**DISKE01.ZIP** (requires 64K free memory)

Contains the FIREFORM source programs in BASIC and a file with information on running the FIREFORM program.

**DISKE02.ZIP**

Contains the FIREFORM program documentation.

**DISKF01.ZIP** (requires 464K free memory, a math coprocessor is REQUIRED, an 80286 or 80386 computer is recommended.)

Contains part 1 of the compiled version of the FAST program.

**DISKF02.ZIP** (requires DISKF01)

Contains part 2 of the compiled version of the FAST program.

**DISKF03.ZIP** (requires 437K free memory, a math coprocessor is REQUIRED, DISKF01 and DISKF02 are REQUIRED)

Contains the compiled form of the FAST\_IN program. This program is used to create data files for the FAST program.

**DISKF04.ZIP** (requires 494K free memory, a math coprocessor is REQUIRED, DISKF01 and DISKF02 are REQUIRED, an EGA or VGA display is recommended)

Contains the compiled form of the FASTPLOT program. This program is used to great graphical output in conjunction with the FAST program.

**DISKF05.ZIP** (requires 108K free memory, a math coprocessor is REQUIRED, DISKF01 and DISKF02 are REQUIRED)

Contains the thermal data base program to be used in conjunction with the FAST program and excerpts from the FAST Technical Reference Guide.

## APPENDIX C

### CARBON MONOXIDE/CARBON DIOXIDE PRODUCTION

June 16, 1988

MEMORANDUM FOR: Richard G. Gann, Chief  
Fire Measurement and Research Division

From: George W. Mulholland, Head  
Smoke Dynamics Research Group

Subject: Position Paper Regarding CO Yield

The purpose of this memorandum is to provide guidelines in regard to CO yield at various stages of a compartment fire: early, developing, and post-flashover. It is intended that the information be incorporated in various CFR fire models such as Hazard 1. The approach will be to first describe a general scenario in terms of CO generation from a room fire. The scenario will then be compared with the results for four types of large scale fire tests. From this comparison we will develop a first order predictive method for estimating CO yield along with yields of CO<sub>2</sub> and O<sub>2</sub> depletion for the various stages of a compartment fire. Detailed results and suggestions for further work will be included in an appendix.

The proposed scenario evolved from a discussion with a group established to develop an empirical prediction of CO. The group includes Bill Pitts, Sandy Davis, Bill Parker, and Vyto Babrauskas. The scenario consists of three stages of fire growth in an enclosure. The initial stage is the free burning stage with relatively low CO yield. As the fire spreads throughout the room, the inflow of air will not be adequate for free burning conditions. The CO yield will increase by a decade or more as the fire becomes ventilation limited up to flashover. In the post flashover stage, the door flame entrains additional air and burns some of the excess CO so that the net yield leaving the door is similar to the free burn conditions. So if we were to monitor CO yield as a function of time, we would expect initially a low value, then a rapid rise for a short period of time, followed by a return to the initial low value for post flashover. The main questions to be answered are whether this scenario is consistent with the large scale tests and what are the actual yields during the various stages. As we review the results from several tests, we shall be considering in addition to the CO yield, the yield of CO<sub>2</sub>, and the O<sub>2</sub> depletion, since all these gases are important in regard to acute toxicity for people exposed to smoke from a fire.

The first tests to be examined were the mobile home fires carried out by Budnick et al.<sup>1,2</sup>. In this series of burns, gas species and temperature

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<sup>1</sup> Budnick, E.K., "Mobile Home Living Room Fire Studies: The Role of Interior Finish," NBSIR 78-1530.

<sup>2</sup> Budnick, E.K., Klein, D.P., O'Laughlin, R.J., "Mobile Home Bedroom Fire Studies: The Role of Interior Finish," NBSIR 78-1531.

measurements were made both in the burn room and in a room or corridor some distance from the burn room. The first burning object was an upholstered chair for the bedroom fires and a wood crib for the living room fires. In the first case the fire was started by lighting newsprint in a polyethylene wastebasket next to the chair and in the second by a small pan of heptane positioned below the wood crib. The tests included both treated and untreated wood paneling and ceiling material. The pre-flashover CO/CO<sub>2</sub> molar ratio was less than 0.1, but because of the low resolution of the CO meter it is not possible to estimate how much less than 0.1. For four tests that reached flashover, the peak CO/CO<sub>2</sub> molar ratio varied from 0.40 to 0.63 in the room of origin with a yield of CO estimated to be in the range 0.31 to 0.42 g CO/g fuel. The CO reading was 6 - 8% in the burn room and off scale (2% full scale) at the remote location, where the temperature ranged from about 150°C to 250°C for the four tests. The data indicate that the CO concentration is high in the second room and it is possible that there is no loss in CO in going from one room to the other. There is no indication of a decrease in CO at the remote location relative to the CO in the burn room after flashover; however, the fire was suppressed shortly after flashover so there is little post-flashover data.

The second series of tests<sup>3</sup> involved items expected in a computer area including a computer terminal, TV, PVC insulated cables, circuit boards, and an upholstered chair. The tests were performed in a 8'x12' room with a 50 kW gas burner ignition source. In one series of tests, unretarded materials were used and in the other all the materials were flame retarded. In one of the tests with the unretarded materials, the CO/CO<sub>2</sub> molar ratio increased rapidly from a value of about 0.012 at 80 seconds into the test to a peak ratio of about 0.2 as flashover occurred at 141 seconds. This peak value was observed both in the burn room and in the exhaust stack. The peak value of 0.2 persisted for about 250 seconds both in the burn room and in the stack and then decreased as the heat release rate of the fire dropped below 1 MW. So in this case, there is no evidence of conversion of CO to CO<sub>2</sub> as the gases leave the burn room and travel through two subsequent rooms before reaching the hood. The fires with the flame retarded materials did not reach flashover, but still resulted in high CO yield with a peak CO/CO<sub>2</sub> molar ratio of about 0.3 both in the burn room with a temperature of about 375°C and in the stack with a temperature of about 33°C. Even with the relatively small fire intensity, there was significant reduction in the O<sub>2</sub> concentration down to 14% in the burn room during the peak burning. The CO yields averaged over the entire test were about 0.22 and 0.23 g CO/g fuel for the unretarded and retarded tests, respectively.

The third test was performed to simulate the flow conditions in the Southfield, Michigan, fire. For this test, the corridor in Bldg. 205 had been broken up into three rooms, and the 1 m diameter gas burner was located in the center of the room closest to the hood. The flow rate of natural gas was set

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<sup>3</sup> Babrauskas, V., Harris, R.H., Gann, R.G., Levin, B.C., Lee, B.T., Peacock, R.D., Paabo, M., Twilley, W., Yoklavich, M.F., Clark, H.M. "Fire Hazard Comparison of Fire-Retarded and Non-Fire-Retarded Products", NBSIR (number not yet assigned) 1988.



to give a heat release rate of about 4 MW. The CO/CO<sub>2</sub> molar ratio was about 0.6 in the burn room and dropped to about 0.04 in the stack. There may be two reasons why the CO was converted to CO<sub>2</sub> in the stack in this case. First, the flames at flashover went through the doorway directly into the stack allowing good mixing with fresh air, while in the tests described above, the flames impinged on the ceiling of the corridor. The methane flame might be similar to flames escaping through a window in an actual fire. The second reason is that the fire is more intense with a heat output of 3 MW compared to 1.3 MW for the unretarded computer room. There is no clear indication of a peak in the CO/CO<sub>2</sub> molar ratio just prior to flashover. A noteworthy feature of this test was the fact that the CO/CO<sub>2</sub> molar ratio for the two adjoining rooms were in the range 0.4 - 0.6. This implies that the CO is not being burned out as it is transported "upstream" to the adjoining rooms. It is almost as if the three rooms can be considered as the burn room in terms of the gas concentration though the temperature is much reduced in the third room, about 250°C compared to 850°C in the burn room.

The final test involved the burning of a 4'x4' and a 4'x8' pieces of PMMA arranged in a T on the wall farthest from the opening to the hood. The PMMA was 1/2 inch thick, and the room, 8'x12' and 8' high, opened into the large hood in Bldg. 205. In this case the fire intensity became large with a heat release rate of about 2 MW and room temperature up to about 1000°C. In 110 seconds the CO/CO<sub>2</sub> molar ratio increased from 0.04 to 1. The CO concentration exceeded the CO<sub>2</sub> concentration in the room by about 20%; however, in the stack the ratio went from a peak value of about 0.28 to a value of about 0.03. The peak width was about 100 seconds. Again, the conversion of CO to CO<sub>2</sub> was probably enhanced by the flames at flashover going directly into the stack.

How do these results compare with the scenario described above? A key question is do the free burn results for CO yield apply to the post-flashover conditions remote from the burn room? The simple answer is no. For both the mobile home fire and the computer room fire, the CO/CO<sub>2</sub> molar ratio remained high remote from the fire even in flashover conditions. In fact, for the computer fire, the ratio was essentially unchanged going from the burn room to the stack. In the case of the Southfield, Michigan simulation fire, it was found that the CO/CO<sub>2</sub> molar ratio was only slightly less in a room separated from the burn room by a second room. Based on information available at this time, the most likely scenario is a rapid increase of the CO/CO<sub>2</sub> molar ratio as the fire becomes ventilation limited. The CO/CO<sub>2</sub> molar ratio will remain at a relatively constant and high value even during flashover.

We recognize that there could be circumstances under which a lower value of the CO/CO<sub>2</sub> molar ratio could occur. If there were a very intense fire in a small room that opened onto a large vestibule, the rapid mixing of the fire plume leaving the room with the air outside could result in combustion of a large fraction of CO to CO<sub>2</sub> thus reducing the CO yield.

The large scale tests are of limited use in regard to providing accurate measurements of CO emission in the free burning stage of burning because of the low resolution of the instruments used. It is apparent that the CO yield is a factor of ten less than the ventilation controlled burning but that is about the limit of resolution of the results. We recommend that the results

from the furniture calorimeter or cone calorimeter be used in this case. A table of values is provided in the appendix. The values are typically in the range 0.001 to 0.05 g CO/g fuel.

For the mobile home burns involving wood paneling and wood ceilings, the average CO/CO<sub>2</sub> molar ratio is 0.50 and the average CO yield is estimated to be 0.36 g CO/g wood burned based on carbon balance. The results are relatively insensitive to whether the first item ignited is a wood crib or chair or whether the fire is in the bedroom or the living room. The yields of CO<sub>2</sub> and O<sub>2</sub> depletion (the loss in O<sub>2</sub> mass per gram of fuel consumed) are 1.1 and 0.9, respectively. These results are to be compared with Beyler's<sup>4</sup> results for the burning of a crib made up of Ponderosa pine at an equivalence ratio of about 1.2. The high value of the equivalence ratio was obtained by adjusting the height between the crib and the collection hood to reduce the amount of air entrained. Beyler obtained a CO/CO<sub>2</sub> molar ratio of 0.23 and a CO yield of 0.15 g CO/g fuel. Both of these numbers are somewhat less than half the values observed in the full scale test. The higher values obtained at large scale may result from several factors:

1. A larger equivalence ratio at large scale.
2. Over estimate of CO yield in large scale as a result of not accounting for unburned hydrocarbons in the analysis (see appendix for discussion of how yields are estimated).
3. Unburned hydrocarbons may be converted to CO in sampling line in NBS tests causing an overestimate of the CO yield (This source of error was pointed out by Beyler<sup>3</sup>).

Another study of interest in regard to CO emission is Tewarson's<sup>5</sup> review of existing wood data in which he reports CO yield as high as 0.6 g CO/g fuel for an equivalence ratio of about 2. His correlation for the yield of CO<sub>2</sub> and O<sub>2</sub> depletion are in agreement with the results for the mobile home fires.

We recommend yields of CO, CO<sub>2</sub>, and O<sub>2</sub> depletion equal to 0.3, 1.1, and 0.9 g/g fuel, respectively, for post flashover conditions for an enclosure where the primary burning components are wood. The value for CO is close to the average value for the mobile home fires, is about a factor of two higher than Beyler's<sup>3</sup> results and Tewarson's<sup>4</sup> correlation and is about a factor of two less than the largest values reported. One should use the recommended value with the point of view that it has about a factor of two uncertainty. The important point is that this value is a factor of 100 times larger than the free burn value for wood and should provide a much more realistic basis for evaluating the hazard using a model such as Hazard I.

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<sup>4</sup> Beyler, C.L., "Major Species Production by Solid Fuels in a Two Layer Compartment Fire Environment," Proceedings of First International Symposium on Fire Safety science, C. Grant and P. Pagni ed., Hemisphere Pub., New York, 431-440 1986.

<sup>5</sup> Tewarson, A., "Fully Developed Enclosure Fires of Wood Cribs," Twentieth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., 1555-1564, 1985.

For enclosure fires involving materials commonly found at a computer work station such as a computer console, TV monitor, electrical cables, and an padded chair, we recommend the following values for the post flashover yields of CO, CO<sub>2</sub>, and oxygen decrement: 0.2, 1.5, and 1.8 g/g fuel. These values might also be used as a first estimate for fires involving primarily plastics with the exception of PMMA and other oxygen containing plastics. The study by Beyler<sup>3</sup> indicates that the CO emission of fuels containing oxygen is larger than for non-oxygen containing fuels, and as a first estimate we recommend using the values obtained for wood for oxygen containing plastics.

The recommendations given above are appropriate for rooms in a house or office opening into a corridor or another room with the same ceiling height. If the room opens to a large vestibule where efficient mixing of the fire plume and air can occur without encountering a surface, then the appropriate values for the various yields for post-flashover conditions would be the free burn results. There will be a period of time, perhaps on the order of 50-100 seconds, of enhanced CO yield as the fire develops from the initial stage of being ventilation controlled up to flashover.

# SUMMARY OF RESULTS

Test	Peak HRR, MW	Peak Values in Burn Room				Peak Values in Adjoining Room or Stack			
		$\Delta O_2$ vol %	CO vol. %	CO <sub>2</sub> vol. %	CO/CO <sub>2</sub> molar	T °C	$\Delta O_2$ vol. %	CO vol. %	CO/CO <sub>2</sub> T °C
Mobile Home <sup>b</sup>									
Bed. #4	-	15.8	7.3	14.3	0.51	760	8.6	≥2.0	-
Bed. #5	-	16.6	6.0	14.9	0.40	690	9.8	≥2.0	-
Liv. #1	-	13.2	8.0	17.4	0.46	680	8.5	2.0	-
Liv. #7	-	16.4	6.9	11.0	0.63	700	16.4	2.0	-
Liv. #3	-	6.5	0.7	6.9	0.10	550	6.5	0.9	-
FRCA <sup>c</sup>									
FRCA-04(N1)	1.3	19.0	2.8	15.0	0.19	780	2.8	0.4	0.18
FRCA-05(FX1a)	0.4	7.4	1.3	4.2	0.31	375	0.9	0.14	0.3
Southfield <sup>d</sup>	3-4	20.5	4.4	8.2	0.6	800	8.5 <sup>e</sup>	0.16	0.04
							17.0 <sup>f</sup>	3.2	0.44
PMMA Wall Fire	2.0	>20	14.5	12.5	1.2	1000	4.5	0.4/0.18	0.25/0.02
									200

<sup>a</sup>  $\Delta O_2$  refers to the decrease in oxygen concentration.

<sup>b</sup> Mobile Home Studies by Budnick et al. (ref. 1 and 2). Bed. #4 and Bed #5 refer to tests initiated in the bedroom with unretarded wood paneling and ceiling material and retarded wood, respectively. Liv. #1 and #7 refers to fires initiated in the living room with unretarded and retarded wood paneling and ceiling materials, respectively. For Liv. #3, the walls were wood and the ceiling gypsum board.

<sup>c</sup> Enclosure fire tests involving a computer terminal, padded chair, PVC cables, TV, and other items commonly found in a computer work area carried out by Babrauskas et al. (ref. 3). FRCA-04 and FRCA-05 refer to tests involving non-retarded items and and retarded items, respectively. The results are tabulated for the burn room and the exhaust stack.

<sup>d</sup> Methane burner located in "cascade" room closest to stack to simulate fire intensity and flow pattern occurring during the Southfield, Michigan, fire.

<sup>e</sup> Stack results.

<sup>f</sup> Results two rooms upstream of the fire.

<sup>g</sup> The first value is the peak value observed in the stack and the second value corresponds to post flashover. The PMMA was burned in a T configuration in a room opening into the large hood.

CO, CO<sub>2</sub>, and ΔO<sub>2</sub><sup>a</sup> Yields for Large Scale Tests

Test	<u>g CO/g fuel</u>	<u>g CO<sub>2</sub>/g fuel</u>	<u>g ΔO<sub>2</sub>/g fuel</u>	<u>location<sup>b</sup></u>
Mobile Home				
Bed. #4 <sup>c</sup>	0.36	1.2	1.0	Bed.
Bed. #5	0.31	1.1	0.9	Bed.
Liv. #1	0.35	1.2	0.7	Liv.
Liv. #7	0.42	1.1	1.1	Liv.
Liv. #3	0.10	1.6	1.1	Liv.
FRCA				
FRCA-04 (N1)	0.22	1.5	1.8	Stack
FRCA-05 (FX1a)	0.23	2.1	2.5	Stack
Southfield,	0.54	1.9	3.3	2 rooms
natural gas	0.06	2.7	3.7	upstream
PMMA wall fire	0.75	1.0	1.3	Stack
	0.28	1.1	1.3	fire room
	0.03	2.2	1.5	stack(peak)
				stack(stea.)

<sup>a</sup> ΔO<sub>2</sub> refers to the decrease in the oxygen concentration.

<sup>b</sup> The yield is computed based on the gas composition at this location.

<sup>c</sup> The yields of CO, CO<sub>2</sub>, and ΔO<sub>2</sub> are calculated based on the assumption that all the carbon from the fuel leaves the fire region in the form of CO or CO<sub>2</sub>. The other assumption is that the fuel burned is 47% by weight carbon. This number is obtained from elemental analysis of sugar pine. The yields will represent an upperbound, since under reduced ventilation it is expected that some unburned hydrocarbons will leave the combustion zone.

CO Yield Under Free Burning Conditions

<u>Fuel</u>	<u>Molar CO/CO<sub>2</sub></u>	<u>g CO/g CO<sub>2</sub> fuel</u>	<u>Reference</u>
methanol	0.001	0.001	Friedman, 1st In't Symp.
wood	0.002	0.002	Friedman
n-heptane	0.003	0.006	Friedman
PMMA	0.007	0.010	Friedman
Prudhoe Bay	0.025	0.05	NBS cone
crude oil			
Rigid polyurethane	0.04	0.06	Friedman
foam			
PVC	0.17	0.13	Friedman
Benzene	0.18	0.32	Friedman
toluene	0.31	0.23	Beyler, Phd. thesis

Comparison Of CO Results for Enclosure Fires  
and Steady State Fires

Fuel	Enclosure Fire		Steady State Fire	
	molar CO/CO <sub>2</sub>	g CO/g fuel	molar CO/CO <sub>2</sub>	g CO/g fuel
wood	0.5	0.36	0.23 <sup>a</sup> 0.28	0.15
PMMA	1.2 <sup>b</sup>	0.75	0.21 <sup>a</sup> 0.25	0.19
Natural gas	0.6 <sup>b</sup>	0.61	0.29 <sup>c</sup>	0.21

<sup>a</sup> Results obtained by Beyler.

<sup>b</sup> Results in burn room.

<sup>c</sup> Results obtained by Zukoski.

Comments Regarding Future Large Scale Experiments

1. In most large scale tests that have been run at NBS, the CO meters have not been sensitive enough for obtaining quantitative data during the free burning stage. It may be necessary to use two CO meters to cover the wide range in CO concentration occurring during a test.

2. There is virtually no data on total hydrocarbon concentration during large scale burns. The concentration of unburned hydrocarbons is expected to become significant during the ventilation limited burning stage. I believe there is a need to modify Parker's pyrocat apparatus for such application or to calibrate a commercially available device for this purpose. It is not possible to obtain an accurate CO yield without this information.

3. There is much uncertainty regarding the burnout of CO in the post flashover environment. There is a need for well planned experiments including measurements in the burn room, in the flame leaving the door, and in the exhaust stack as a function of the ventilation conditions, room size (this will effect the residence time) and fire intensity (fuel loading). A useful first step would be a series of gas burner experiments in the burn room opening onto the corridor as a function of the fire intensity (0.5 - 2.5 MW), vent area, and door height.

4. There is a need for accurate measurement of the air flow entering into the room as well as the mass loss rate of the fuel to estimate a global equivalence ratio.

5. Beyler has questioned the validity of data obtained with uncooled probes. He is concerned about the conversion of hydrocarbon into CO in the probes. There is a need to investigate this issue and to devise a suitable probe for gas and smoke sampling in a high temperature environment.

November 1, 1989

MEMORANDUM FOR: William Pitts, Leader  
CO Priority Project

From: George Mulholland *GUM*  
Smoke Dynamics Research Group

Subject: Comparison of Predicted CO Yield with Results from Fire  
Reconstruction of Sharon, PA Fire

A memo from Mulholland to Gann, dated June 16, 1988, contained a prediction of CO yield for pre and post-flashover burning of a room where the primary item burning was wood. We shall term this model for CO yield the Two Level CO model. The model is based on the studies by Beyler<sup>1</sup> and by Toner, Zukoski, and Kubota<sup>2</sup> regarding the dependence of CO yield on the equivalence ratio. They observed a relatively constant and small CO yield for fuel lean conditions, a rapid increase to a value in the range 0.15 - 0.3 g CO/g fuel consumed as the equivalence ratio is increased from 0.5 to 1.5, and then a relatively constant value for larger equivalence ratios. The Two Level CO model represents a simplification of the observed behavior with one CO yield value for pre-flashover conditions and a second value for flashover and post-flashover burning, which would correspond to fuel rich burning with equivalence ratio greater than unity. The actual value used in the Two Level CO model for the post-flashover yield is based on a series of mobile home fires carried out by Budnick et al.<sup>3</sup> (3,4). The model predictions for wood burning are given below:

	<u>Molar CO/CO<sub>2</sub></u>	<u>g CO/g wood</u>
Pre-flashover	0.002	0.002
Post-flashover	0.5 <sup>4</sup>	0.3

<sup>1</sup> Beyler, C.L., "Major Species Production by Solid Fuels in a Two Layer Compartment Fire Environment," Proceedings of First International Symposium on Fire Safety Science, C. Grant and P. Pagni ed., Hemisphere Pub., New York, 431-440, 1986.

<sup>2</sup> Toner, S.J., Zukoski, E.E., and Kubota, T., "Entrainment, Chemistry, and Structure of Fire Plumes," NBS-GCR-87-528, 1987.

<sup>3</sup> Budnick, E.K., "Mobile Home Living Room Fire Studies: The Role of Interior Finish," NBSIR 78-1530.

Budnick, E.K., Klein, D.P., O'Laughlin, R.J., "Mobile Home Bedroom Fire Studies: The Role of Interior Finish," NBSIR78-1531.

<sup>4</sup> On page 4 of the memo referred to above, the recommended yields of CO, CO<sub>2</sub>, and O<sub>2</sub> depletion are given as 0.3, 1.1, and 0.9 g/g fuel, respectively, for post flashover conditions for an enclosure where the primary burning

The fire reconstruction of the Sharon, PA fire provided an ideal opportunity to test the validity of the Two Level CO model. First, the only burnable material was wood. Secondly, the magnitude of the fuel loading in the kitchen and the size of the kitchen window were chosen to insure fuel rich burning for an extended duration. Thirdly, there was little opportunity for the CO leaving the kitchen and going into the hallway to be converted to CO<sub>2</sub>, because there was very low oxygen concentration in the hallway except at early time.

The fuel assembly, illustrated in Figure 1, consisted of an array of eighteen cribs, weighing a total of 75 kg, with plywood sheets, weighing 109 kg, positioned as walls, floor, and as fins between the rows of cribs. The entire fuel assembly was supported on a load cell in the "kitchen" as indicated in Figure 2.

At the start of the burn, the kitchen door was open. The fire was ignited using 2 liters of heptane in narrow troughs located under the cribs. The fire intensity grew rapidly approaching flashover conditions at 130 seconds, at which time the kitchen "window" was opened simulating the window breaking in the actual fire. The peak mass loss rate was 0.32 kg/s occurred 160 seconds after ignition after which there was a steady decrease to 0.17 kg/s at 600 seconds (See Figure 3). For a well ventilated wood burn, a mass loss of 0.32kg/s would correspond to a heat release rate of about 4.2 MW; however, the low oxygen concentration measured in the gases leaving the room indicates that the burn was ventilation limited as was planned.

Leaving the kitchen, the combustion gases moved down a hallway, up the stairs, and then into either the south bedroom, which had a window opened 0.15 meters, or the north bedroom (See Figure 4). As indicated in Figure 5, the CO concentration in the south bedroom (probe located in the center of the bedroom, 0.3 m from ceiling) reached a first peak around 200 seconds, dipped slightly, and then reached a second peak around 400 seconds. The opening of the downstairs window at 130 seconds apparently increased the ventilation rate to the point where the fire was no longer as fuel rich thus resulting in a sudden decrease in the CO production. This momentary decrease in CO production is more apparent at the door soffit in the downstairs hallway where the CO concentration decreases from 8 % to less than 5 % (volume % of dry air) before increasing again to 8 % as shown in Figure 6. Because of the large fuel load, the burning rate apparently increased rapidly after the window was opened so that the fire was again fuel rich and the CO yield consequently increased. One inconsistency in this interpretation of the second CO peak is that the mass loss rate of the fuel based on the load cell measurements is

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components are wood. No recommended value for molar CO/CO<sub>2</sub> ratio is specifically given. From the results of Budnick *et al.*<sup>3</sup>, which are the basis of the yields given above, an average molar CO/CO<sub>2</sub> ratio of 0.5 is obtained. We take this as the recommended value. It should be noted that a slightly lower value of the CO/CO<sub>2</sub> ratio of 0.43 is obtained from the CO and CO<sub>2</sub> yields of 0.3 and 1.1 g/g fuel consumed, respectively, given above. The reason for the discrepancy between the two values of the CO/CO<sub>2</sub> ratio is that the recommended CO yield of 0.3 is slightly lower than the actual average value of 0.36 obtained from the tests.



decreasing or constant rather than increasing over the time interval between the two peaks. At this time it is not known whether there is an error in the load cell measurements or whether some other effect such as a changing chemistry of the pyrolysis products or a transient flow phenomenon is responsible for the two peaks.

Since there is not an accurate measurement of the flow through the various doors and windows, it is not possible to compute the CO production per gram of fuel consumed for comparison with the prediction again. Instead, we must rely on the molar ratio  $\text{CO}/\text{CO}_2$  for comparison with the predicted value. The  $\text{CO}_2$  data at the door soffit is questionable, since the meter could not be zeroed at the start of the test. Consequently our analysis will focus on the results for the north and south bedrooms. The  $\text{CO}/\text{CO}_2$  ratios for the north and south bedrooms track quite well as shown in Figure 7 with the north bedroom, which had the closed window, tracking about 20 % higher than the south bedroom. The peak value of this ratio was 0.37 in the south bedroom at 160 seconds, and the average value of  $\text{CO}/\text{CO}_2$  over the interval from 160 to 420 was 0.29. The molar ratio  $\text{CO}/\text{CO}_2$  decreases rapidly for times greater than 420 seconds. The corresponding values in the north bedroom were 0.5 and 0.35, respectively.

The peak values of the molar ratio  $\text{CO}/\text{CO}_2$  observed in the tests are similar to the Two Level CO model prediction of 0.5; however, the mean values are significantly lower and are in better agreement with the value of 0.28 obtained by Beyler for crib burns in a hood. The lower  $\text{CO}/\text{CO}_2$  molar ratio observed in the Sharon test compared to the Two Level CO model prediction might be due to the increased ventilation resulting from the breaking of the window. In any event,  $\text{CO}/\text{CO}_2$  ratios in the range 0.25 to 0.5 seem to bracket the range of values observed for ventilation limited burning of wood. A listing of the predicted and measured results are given in Table I.

There are a couple of simplifications in the previous discussion. The  $\text{CO}/\text{CO}_2$  ratio increases from pre-flashover to post-flashover. The  $\text{CO}/\text{CO}_2$  ratio for the gases leaving the burn room will be higher than in the upstairs bedroom, because as the hot gases flow into the bedroom, cooler air with a lower  $\text{CO}/\text{CO}_2$  ratio will be entrained into the upper layer. This effect will cause a lowering of the  $\text{CO}/\text{CO}_2$  ratio.

A second assumption is that there are no chemical reactions affecting the CO concentration taking place once the gases reach the doorway; that is, it is assumed that there is no conversion of CO to  $\text{CO}_2$  or unburned hydrocarbons to CO as the hot gases leave the burn room. As indicated above, this is probably a reasonable approximation for the upstairs, since there is relatively small amount of oxygen available for reaction and the temperature is less than  $400^\circ\text{C}$ . This is a poor approximation for the gases escaping through the window as discussed below.

Measurements of the  $\text{CO}/\text{CO}_2$  ratio were also made in the large stack which collected the gases released through the window in the kitchen. Burning outside of the window was observed. This was reflected in the measured  $\text{CO}/\text{CO}_2$  ratio being about 0.05 over the time period 300 to 500 seconds as indicated in Figure 8 compared to values of about 0.3 for the bedrooms. (Two  $\text{CO}_2$  instruments were used for monitoring the  $\text{CO}_2$  concentration in the stack and

are identified as Stack ( $\text{CO}_2$ , a) and Stack ( $\text{CO}_2$ , b) in Fig. 8). This suggests that burning outside the room can significantly reduce CO emissions. There is a significant increase in the CO/ $\text{CO}_2$  ratio in the stack for the time interval between 600 and 800 seconds. This may result from the retreat of the flame into the kitchen so that there is no combustion outside the window. There are two troublesome aspects to the data at long time: First, the 50% discrepancy between the results in the stack obtained with two different  $\text{CO}_2$  meters and secondly the fact that the CO/ $\text{CO}_2$  ratio for long times is larger in the stack than in the bedroom. It is possible that a slight drift in the gas analyzers, which are being used near their sensitivity threshold, is responsible for the differences.

### Conclusion

The Sharon, PA Fire Reconstruction clearly indicates that fuel rich burning of wood leads to high levels of CO emission. The Two Level CO model predicts CO/ $\text{CO}_2$  ratio of 0.5 compared to measured values in the range 0.25 - 0.5. The agreement is encouraging given the global character of the model and the varying equivalence ratio resulting from the opening of the window. I believe it is correct to say that the Two Level CO model captures the essence of the CO yield during the test.

The first order comparison between the Two Level CO model and the Sharon Test assumes a steady state condition. A quantitative analysis capable of treating the transient evolution of the flow and gas concentration with the Two Level CO model for the source term is needed. This is necessary to study the sensitivity of the CO/ $\text{CO}_2$  ratio in the bedrooms to the transient fire development. In regard to this fire test, the issue is, given a developing fire with a CO/ $\text{CO}_2$  source ratio of 0.002 for the first 100 seconds and a CO/ $\text{CO}_2$  ratio of 0.5 for the following 300 seconds, what would be the predicted CO/ $\text{CO}_2$  ratio in the bedroom as a function of time? Our steady state analysis assumes that the CO/ $\text{CO}_2$  ratio in the bedroom is the same as at the source. "Fast" could be used to carry out such an analysis.

While the Sharon Test represents a milestone test in regard to CO yield, there is a great need for improved gas analysis and sampling for future tests. Specific issues relevant to the Sharon test are listed below:

1. No gas sampling in the burn room because of lack of adequate high temperature probe. Such data is needed to assess whether CO is being converted to  $\text{CO}_2$  as the gases flow out the doorway.
2. Inconsistent readings of the two  $\text{CO}_2$  meters in the large stack (associated with downstairs window) and anomalous CO results in the stack. The appropriateness of the stack gas meters for the expected low concentrations of CO and  $\text{CO}_2$  should be evaluated.
3. No measurement of unburned hydrocarbons or of water. There is a need to measure the local equivalence ratio in the burn room.
4. There is concern about the reliability of the total mass loss measurement.

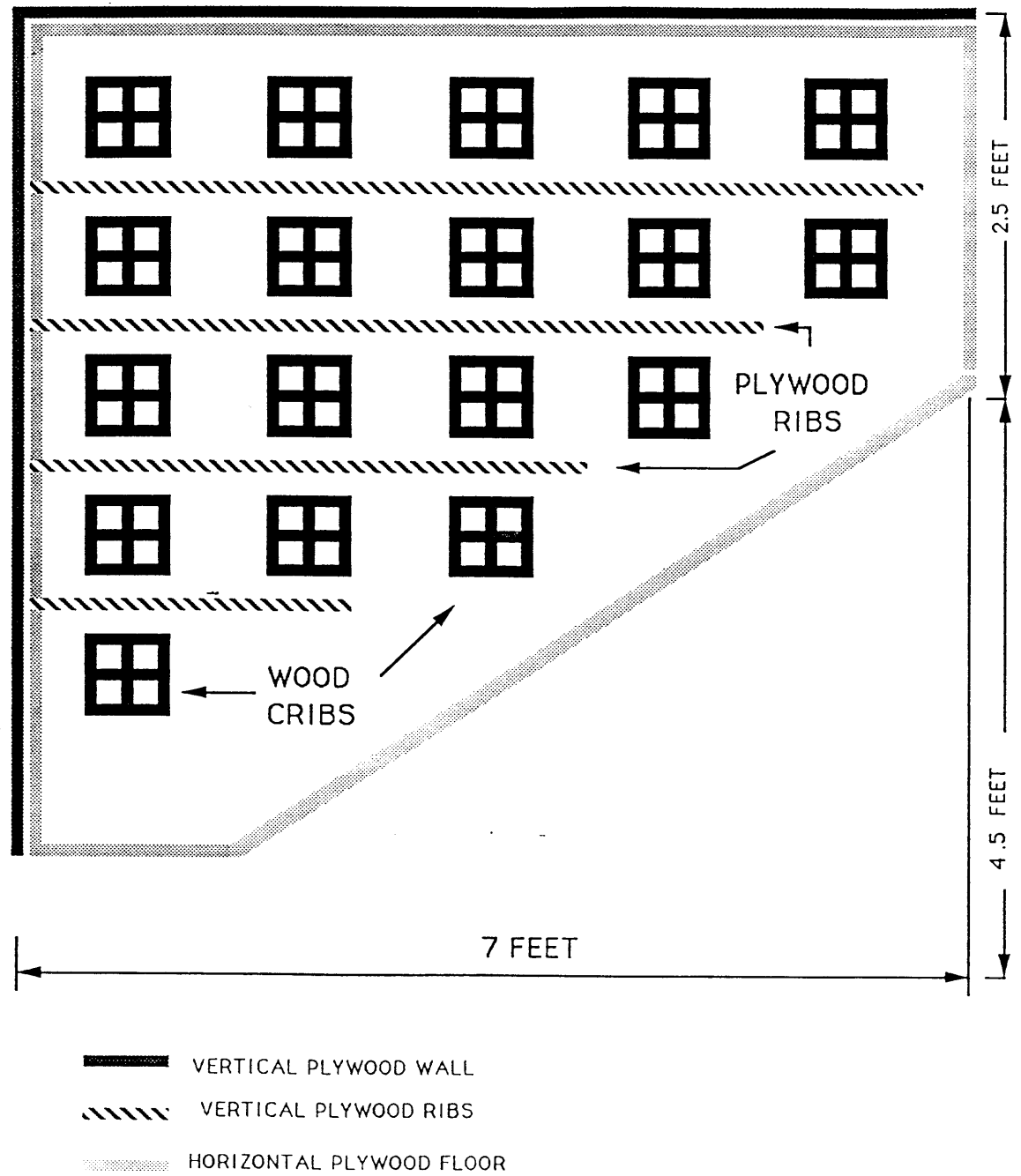
Table I CO Comparison: Predicted Result, Sharon Fire Reconstruction  
Result, and Beyler's Hood Result

Prediction/Test	Molar CO/CO <sub>2</sub>	Reference
Two Level CO model		Mulholland memo to Gann,
Pre-flashover	0.002	6-16-89
Post-flashover	0.5	
Sharon Fire		
Reconstruction		
South bedroom	0.37, peak; 0.29, average	
North bedroom	0.50, peak; 0.35, average	
Stack	0.15-0.25, peak after opening window	
Stack, post-flashover	0.05-0.07, average from 300-500 seconds	
Crib burn of Ponderosa	0.28 <sup>5</sup>	Beyler
pine in a hood, fuel		
rich		

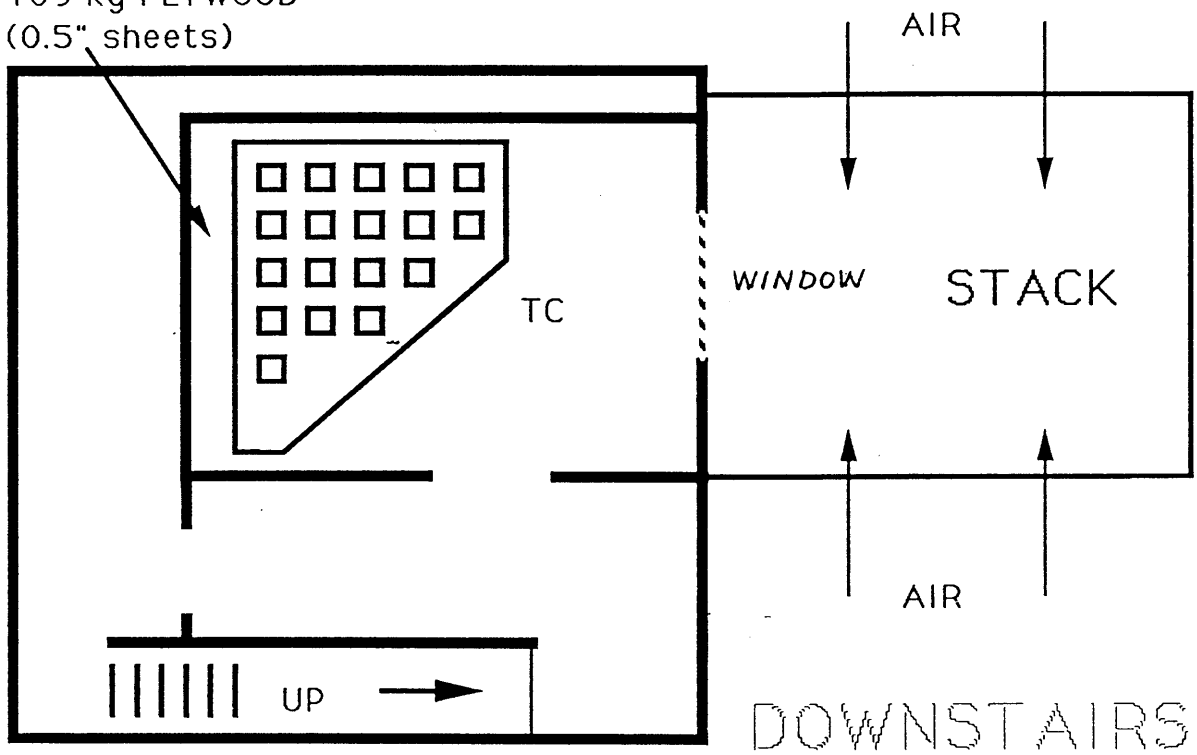
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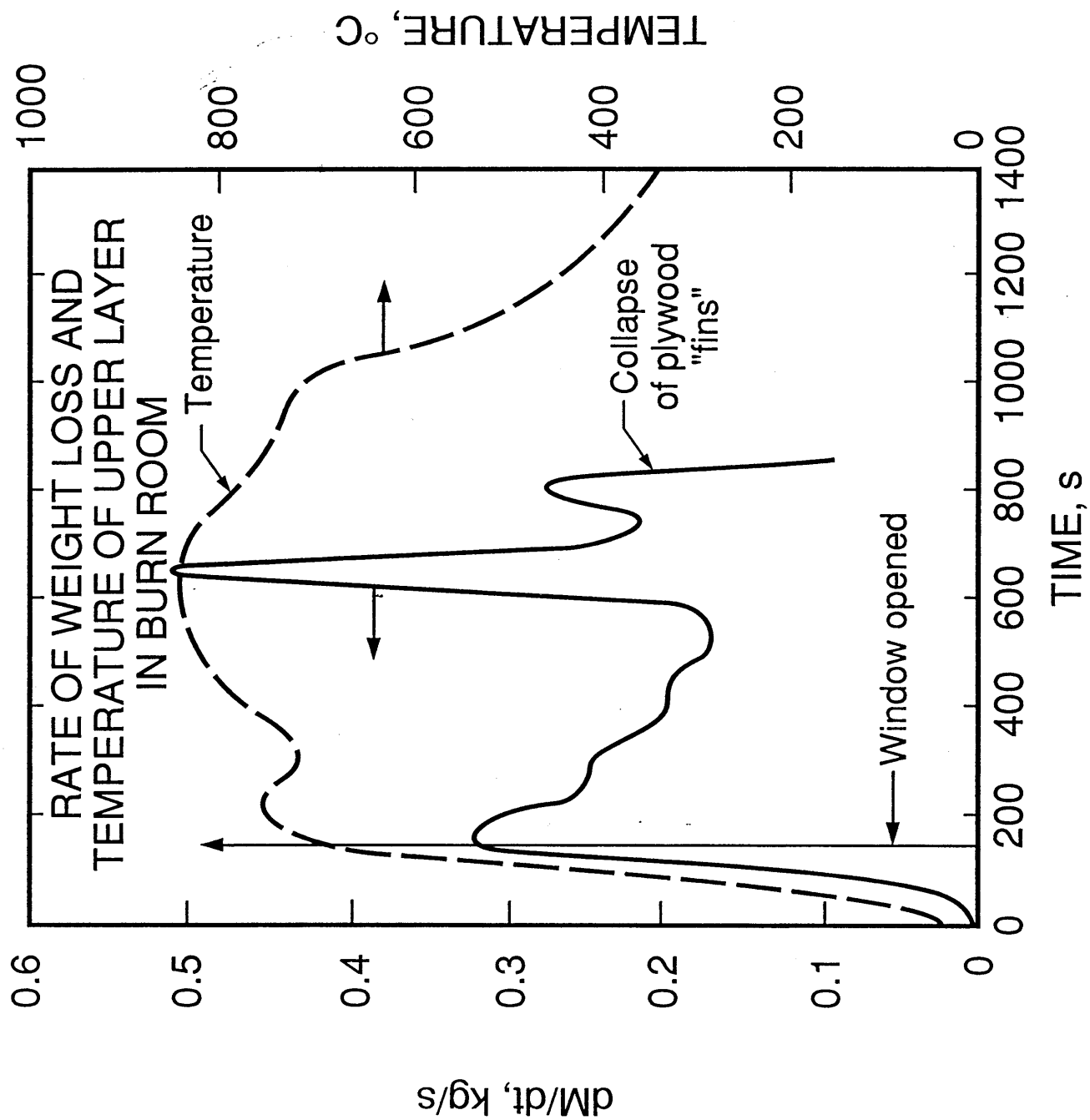
<sup>5</sup> The value for the molar ratio CO/CO<sub>2</sub> given in the 6-16-88 memo from Mulholland to Gann was given incorrectly as 0.23.

# FUEL ASSEMBLY

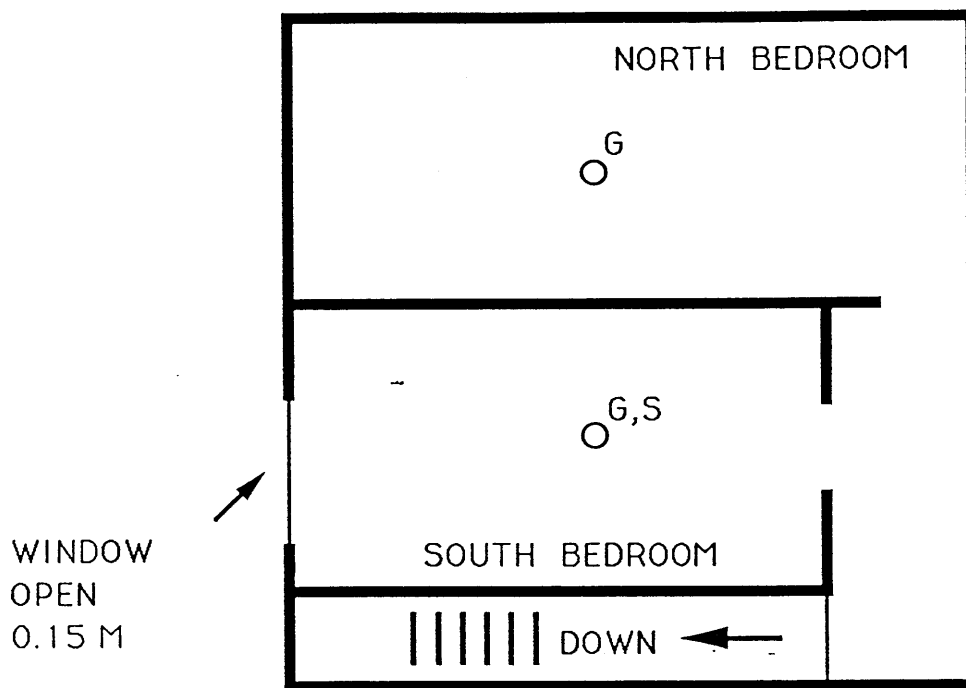


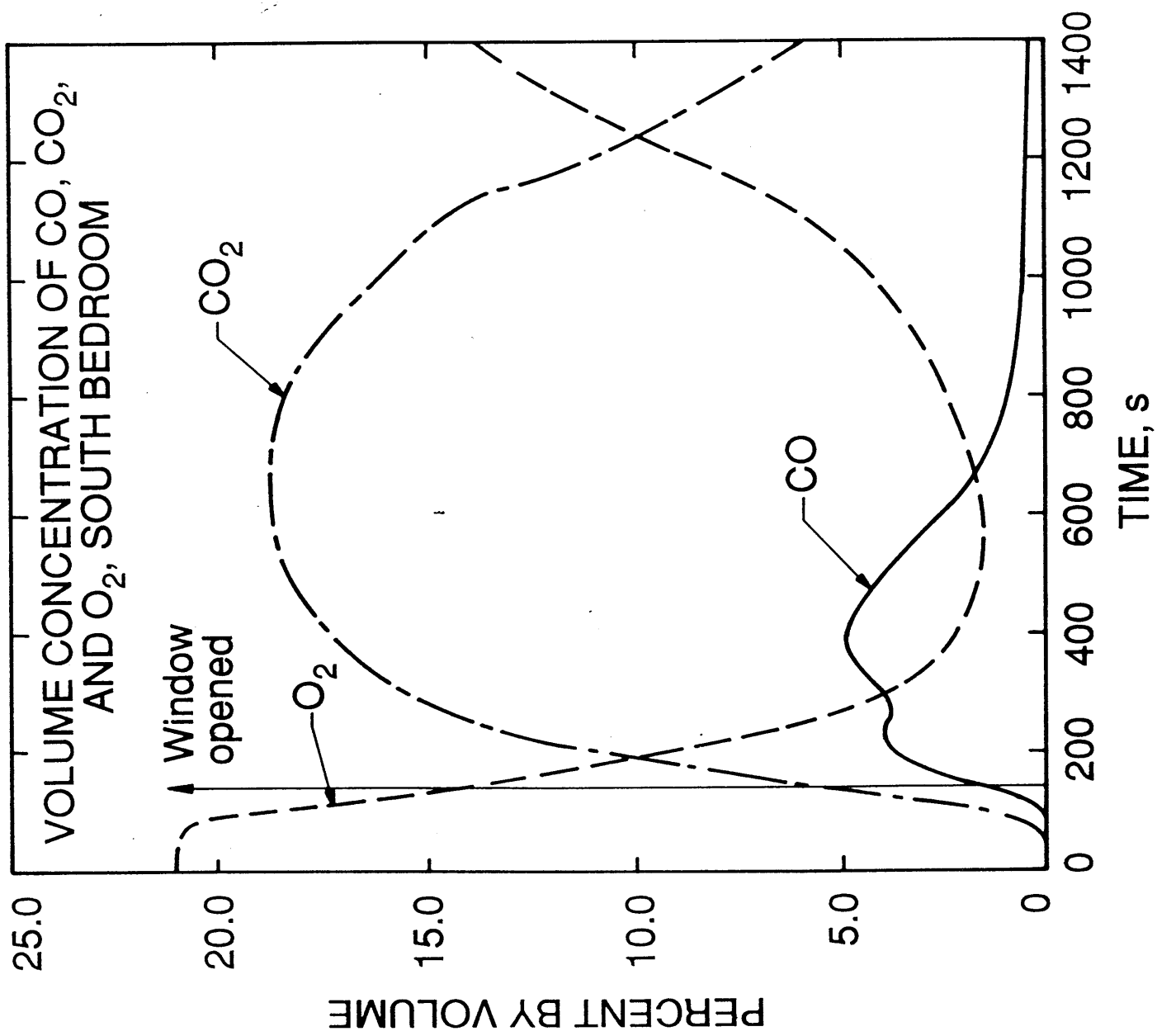
75 kg CRIBS  
109 kg PLYWOOD  
(0.5" sheets)



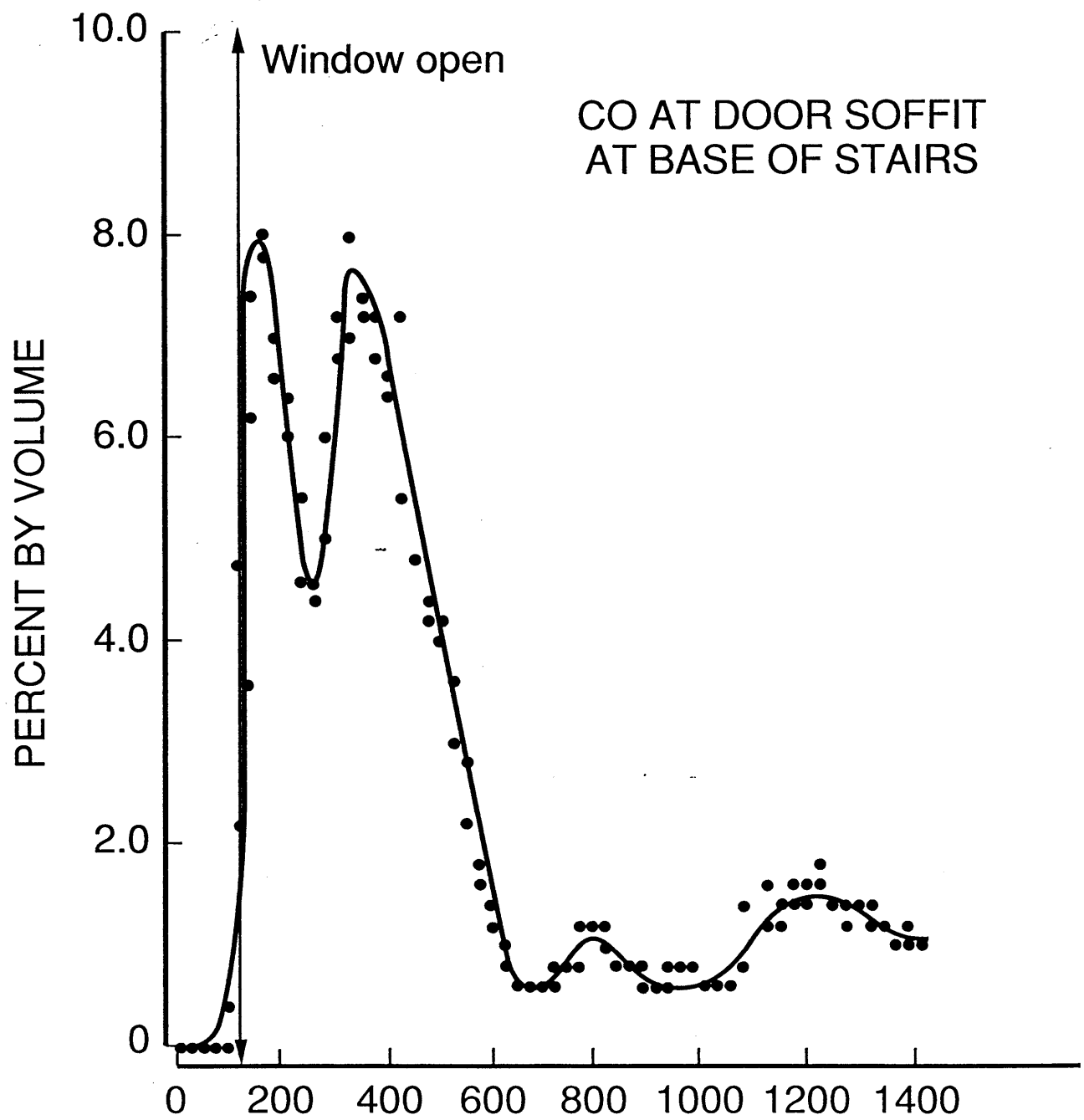


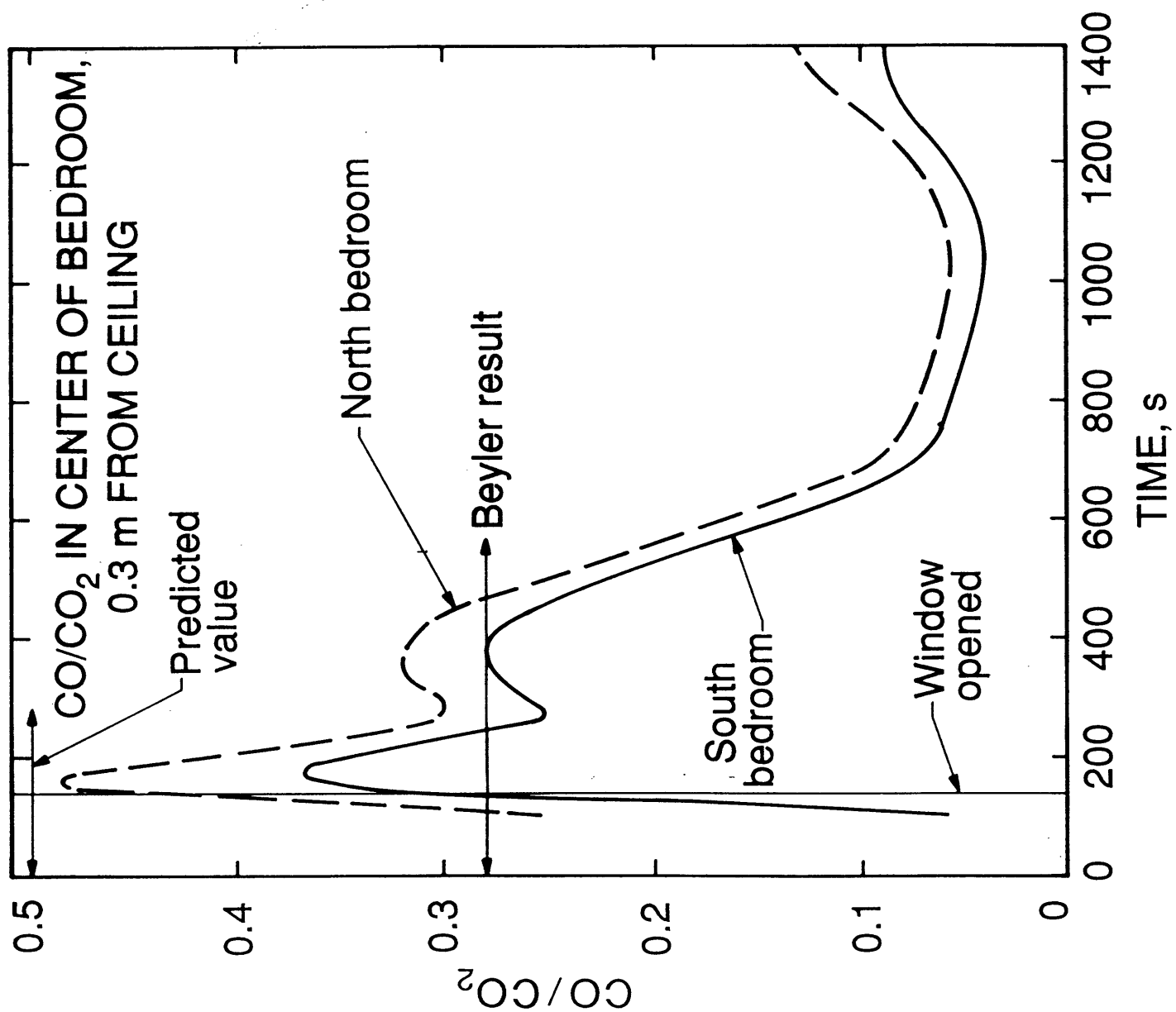
## UPSTAIRS LAYOUT

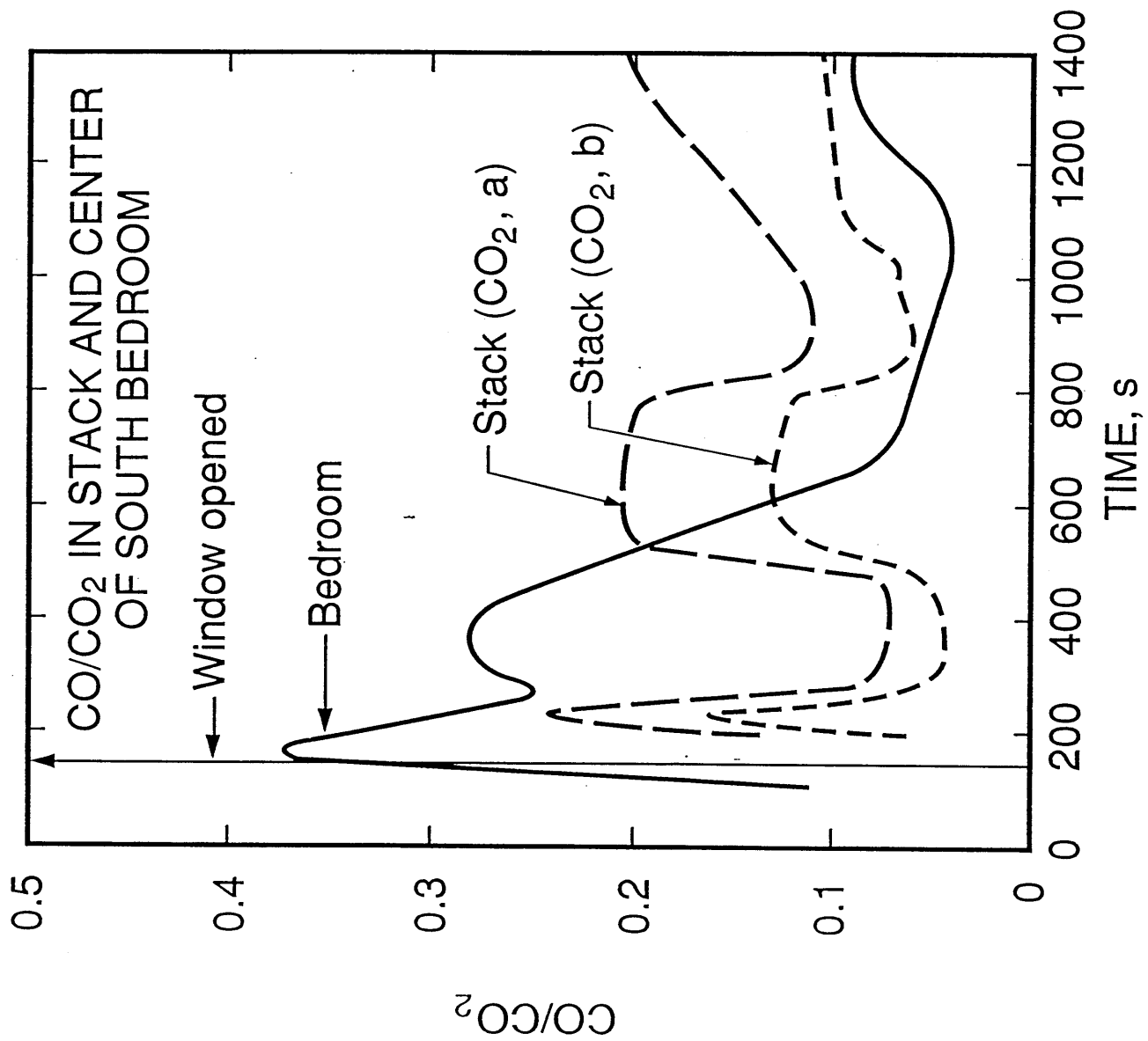














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